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Applications of Tethers in Space

Workshop Proceedings
Volume 1

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NASA
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Scientific and Technical
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1986

PREFACE

The Applications of Tethers in Space Workshop was held in Venice, Italy during the period October 15-17, 1985. The Hotel Excelsior, located on the island of Lido, provided outstanding accommodations for the workshop, which was jointly sponsored by the Italian National Space Plan, National Research Council, and the National Aeronautics and Space Administration, Office of Space Flight, Advanced Programs Division. Workshop coordination was provided by the Centro Internazionale Congressi and General Research Corporation. Aeritalia generously provided a gala dinner banquet for the workshop attendees and their guests, and the office of the Mayor of Venice hosted a reception at the city hall.

General Research Corporation would like to thank and commend everyone who organized, coordinated, and participated in the workshop. The panel co-chairmen are especially noteworthy in fulfilling their roles of directing and summarizing their respective panels. We are proud to have participated in the workshop and be a part of the advancement of this exciting and challenging field which, as is evident in these proceedings, is evolving into a technically sophisticated and mature science. The complete documentation of this workshop is contained in the Workshop Proceedings, Volumes 1 and 2. The Executive Summary, which contains an abbreviated compilation of the panel summaries, is also provided.

William A. Baracat
McLean, Virginia
March 1986

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FOREWORD

The Tethers in Space Workshop held in Venice, Italy, follows by only two years the one held in Williamsburg, Virginia, in June 1983. Yet, much has happened. The most significant events are: (1) the passing of our beloved leader, Giuseppe Colombo, (2) the announcement by President Reagan of the Space Station as a national goal, and (3) the initiation of several tether demonstration missions, already in hardware development or design phases.

Bepi, whom we call the "Father of Tethers," would be pleased at the pace of this emerging technology. The development of the Tethered Satellite System (TSS), a joint U.S. - Italy project, is on a firm course, with the first launch scheduled for 1988. The announcement of the Space Station goal by the President has provided an anchor for serious studies of the use of tethers on the Space Station. A whole panel session was devoted to this subject at this workshop, and was the second best attended. NASA, Italy, and industry continue to examine the benefits and technological problems associated with placing a tether system on the Space Station. We fully expect to see this happen, although it may be after the Initial Operational Capability (IOC).

Are there other tether and tether related missions that can be flown in the next few years on the Shuttle in addition to the TSS? The answer is yes. NASA, with Italy's involvement, will be verifying the principles of electromagnetic tethers in space to produce power or drag. A series of flight experiments are either hardware ready, or in hardware development. These experiments should enhance the TSS-1 mission, and may use at some point the disposable tether, which itself will require a preliminary demonstration. Looking to the future, there is much interest in the tethered platform, with the tether assisting in platform pointing. NASA's Ames Research Center, again with the Italians, are engaged in a definition study on this, called the Kinetic Isolation Tether Experiment (KITE).

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Our reach in this workshop has not only been to Earth orbit but also to the planets. Serious attention to tether operations near the Moon, Mars, and other planets is underway. Some of these ideas are presented in the workshop proceedings. Although it may sometimes seem that we are getting ahead of ourselves, these applications may be here sooner than we think.

Paul A. Penzo
March 1986

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I

INTRODUCTION

OPENING ADDRESSES

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ORIENTATION AND PURPOSE

Luciano Guerriero
PSN

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It is a privilege and a pleasure for me to welcome such a qualified audience here in Italy and, in particular, the beautiful city of Venice, for this second workshop on the "Applications of Tethers in Space".

Two years ago, the first and very successful workshop on this subject was organized by NASA in the historical town of Williamsburg, Virginia. Now, I am really grateful to NASA and to my good friend Ivan Bekey, that they proposed to have this second workshop in Italy, and have offered to alternate between the U.S.A. and Italy for future editions of this meeting.

It is indeed a nice and friendly way to recognize the role and the efforts that Italy is providing to the development of the initial program and in the exploration of the full potential of tether concepts.

The choice of Venice has for me an additional important meaning: Padua University, 20 miles from here, one of the oldest in Italy and in the world, has for many centuries been the State University of the great and glorious Republic of Venice.

From Padua University came Bepi Colombo, whose ideas have been of such exceptional importance for the development of the tether concept. It is very sad that Bepi, who has been friend and guide for many of us, is not with us anymore. However, I believe that your enthusiasm and your efforts to develop successful applications of the tether concept, is the best homage that can be attributed to his memory.

Now we have to move into the program.

The Mayor of the city of Venice, Mr. Nereo Laroni, was expected to be with us. Unfortunately, he had to modify his schedule. We will meet him tonight, when he will host the reception at the City Hall.

We are glad to have with us Mr. Salvadori, Assessore al Turismo, who will now briefly address the audience, and officially open the meeting.

(Mr. Salvadori's address appears following this presentation)

I have now the honor and the pleasure to introduce the Italian Minister for Science and Technology, Sen. L. Granelli.

Sen. Granelli has the political responsibility for all Italian space activities. I must say that in Italy we are all very grateful to Mr. Granelli for this continuous and determined action in support of the Italian and European space programs.

I like to remember that, under his leadership as President of the Council of the European Space Agency, Europe has adopted very important decisions for the cooperation with the United States on the construction of the future space infrastructure in Low Earth Orbit.

The present cooperation program between Italy and the United States on the Tethered Satellite System, and the perspective of a continuing cooperation on tether applications, have been strongly encouraged and supported by the Italian political authorities.

The presence of Minister Granelli at this meeting is certainly the best evidence of the Italian interest and commitment.

(Mr. Granelli's address appears following this presentation)

Two years ago, the first workshop on the Applications of Tethers in Space, held in Williamsburg, was very successful. At that time many interesting ideas were explored and evaluated.

During the past two years, while preparation of the first flight of the TSS was proceeding and taking us closer to the first and extremely important experimental test of the dynamic and electrodynamic properties of the tether systems, studies have been carried on, both in the USA and in Italy on tether applications.

We would like to verify at this meeting what progress has been made, and to review together where we stand concerning:

- Theoretical and technical feasibility
- Cost effectiveness
- Constraints, in particular in connection with Space Station applications
- Preliminary design
- Possibilities for flight demonstration

We will try to maintain the organization of this meeting as close as possible to the one at Williamsburg.

Today we will have only a plenary session. We will start with a keynote address on the evolution of ideas on tether applications. This will be followed by a presentation of the status of the joint program on the TSS. A tutorial session on tether fundamentals and a survey of tether applications and related technology will occupy the rest of the day.

In the second and third days the participants will be divided into working panels. The panel tasks are similar, but a little more ambitious, than the tasks set for Williamsburg. In particular, these tasks are:

- Identify additional new applications for tethers in space
- Analyze, critique, and evaluate feasibility of all identified tether applications relative to their practicality, cost benefit, and operational requirements.
- Identify those critical design, performance, operational factors and technology advancements that must be included in the evolution of the practical feasibility of each tether application.
- Identify demonstration missions necessary to implement tether applications in space projects.
- Provide recommendations to NASA and PSN/CNR for the continued evaluation and definition of the tether applications identified.

Plenary sessions in the afternoon of the second and third day will be used to present and discuss preliminary findings and recommendations.

The panel co-chairmen are expected to product a final report document before leaving. Thank you.

WELCOME

Augusto Salvadori
City of Venice

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It is with much pleasure that I offer my personal salutation and that of the City of Venice to the illustrious guests participating at this workshop, which is sponsored by NASA and the Italian National Space Plan.

The choice of an Italian seat emphasizes the profound significance intrinsic in the scientific and industrial collaboration between our country and the United States.

The choice of Venice, in particular, of which we are all delighted and proud, enriches this significance. In fact, I believe the intention of the participants can be considered as a recognition of Professor Colombo's work and study. I concur with this feeling, for it was Professor Colombo who originated the proposal that has permitted the extraordinary space applications of tethered satellites.

But let me bring up another consideration: For a long time, there has been the question of the "two cultures", humanistic and scientific. I am convinced that this is not a problem because, when man engages his best energies and his life searching for answers, searching for truth, he discovers himself and he contributes to his heritage. In one word, he makes culture.

Italy and Venice, birthplaces of historical humanism and renaissance, offer hospitality to a symposium of experts in high technology and operators of principal industries. The roots of this workshop lie in common ground with man's work for progress and peace.

OPENING ADDRESS

Luigi Granelli
Minister of Scientific Research and Technology, Italy

We wish to thank the representative of the mayor of Venice for his welcome address to this audience. We are very happy to participate in this workshop which will strengthen the cooperation between the United States and Italy in the field of space exploration and utilization.

We would remind everyone that a basic step of this cooperation is the Memorandum of Understanding for the "Tether" program that was signed in Italy by Mr. Beggs and Professor Quagliariello for NASA and CNR in March, 1984.

We feel that this program has great importance and is a beautiful example of the aforementioned international cooperation. As everyone knows, the tether is a very new system, so new that we could call it the second, or the new, generation of satellites.

The tether was born from an original idea of the lamented Professsor Giuseppe Colombo of the Padova University. This idea is so original that it will be possible to apply many of the tether concepts to the Space Station. To mention only a few of these applications: the capability of generating power, the possibility of assembling large structures in space, and the possibility of generating a variable microgravity environment. Before concluding this brief address to you, we would like to make two points of a general nature. The first one relates to the Italian National Space Plan. We are in the process of adjourning and updating its budget for the next five years. This would be done before December 1986. We have in mind a number of practical projects that will make it possible to increase the Italian space capabilities. The second general point is the cooperation between Europe and the United States. This cooperation is the best way to overcome the difficulties that will certainly be present in the European and American space programs.

In conclusion, we are sure that the results of this workshop will give us new elements for a better definition of the "Tether" application field.

KEYNOTE ADDRESS

Ivan Bekey
Office of Space Flight, NASA Headquarters

It is really heartening to see so many of the tether faithfuls in the room today who are willing to sacrifice and come to a small island away from everything just to talk about the strange things we can do with a string and a ball in space.

It is heartening for several reasons. First of all, when we started the concepts of doing things with balls and strings two and a half years ago, there were only a few. Even at the meeting in Williamsburg, we were only starting to talk about the concepts, whereas now we will be able to talk about a study of results as well as concepts.

So we're making progess. Let's remember that, throughout history, progress was made by small groups of dedicated people who were willing to believe in their causes and faithfully followed them, and they did so in the face of disbelief by even their own colleagues.

This has included explorers, discoverers, lone scientists, religious sects, technicians, tinkerers, and even some courageous politicians. They all had one thing or several things in common. That is, they had initiative. They believed in what they were doing; they were stubborn; they were willing to endure ridicule and some even punishment. In many cases, they also had to have a sense of humor to survive.

Many started here in Italy. In fact, there are some very famous names that you can associate with. Galileo, Columbus, Volta, Marconi, Vermi, Colombo, just to name a few.

And so it really is fitting, as was said by both Professor Guerriero and our representative of the City of Venice this morning, that we should meet here in Italy, and this is where our band of tether faithfuls will begin the second round in our series of workshops. It should give us inspiration, because we really have come a long way.

In the past few years, we have seen some real growth from initial ideas to beginnings of recognition. We have had, and continue to have, a cooperative hardware program. Also, the beginnings of recognition for tether applications, though a bit reserved, include acceptance of some of our ideas.

From the initial identification of some concepts by Professor Colombo many years ago, and the work we have done since, the future applications are beginning to emerge. It wasn't until two and a half or three years ago that we really began to understand what we have. We have something very fundamental in applications of tethers, and many of us are convinced that it will lead to a revolution in the many ways in which we can behave in space and do business in space.

In order to take full advantage of tethers, we have to get very, very fundamental. In fact, we have to get so fundamental that most of us have forgotten how; and we have to go back to first year of college dynamics to remember how. We have to get back to basics.

It is very much like the field of architecture in the 1930's, for example, when designs of buildings were becoming more and more ornate, and beginning to lose their function. Architects became enlightened and finally said, "Less is more." Perhaps it is that way with tethers as well.

We really have to realize that, in our rush to exploit the power of rockets, which has resulted in the heavy cost of free flight in space, we have really forgotten and overlooked something very fundamental. We really have to learn again how to exploit tethers and bodies which are attached by tethers in some very fundamental ways in space.

Not all people in history have forgotten. In fact, there has been some notable exceptions of people who have actually utilized tethers in history and utilized them very successfully. In one example, for instance, David used it very successfully against Goliath; I might say with stunning success.

Now tethers are very powerful tools, and we are just beginning to understand what we can do with them, and the ranks of believers are swelling. It is very heartening to see new faces in the crowd and, hopefully, to see the band of tetherists growing.

We have made a lot of progress since Williamsburg, and perhaps one way in which I judge how much progress we have made is that people don't laugh at me as much any more. They don't give me as many condescending looks. They may still make weak jokes, but nonetheless we have a solid hardware program in the implementation phases between PSN and NASA and a group of international scientific users, who have been formally selected to exploit the initial flight or two.

We have also been quite busy in telling people what we can do with the concept after we have demonstrated that the TSS will work. We have been getting some glowing reports from scientific advisory bodies, from military groups, and from commercial groups that we have made presentations to. Everywhere there's a growing realization that one can do unique things with tethers which one cannot do any other way. Even if there are applications that are not unique, at least they are very interesting, and may perhaps be even more cost-effective than using the conventional approach.

We have identified ways to change orbits without propellants. We have identified ways to generate power without solar arrays. We have identified ways of holding satellites in a fixed orientation relative to each other without propellants or guidance, and many other things.

A most recent and interesting set of applications came out of a mini-workshop we had in Washington less than a month ago. The purpose was to look at planetary applications, both unmanned and manned, in the far reaches of the solar system. Some of these will be explored here at this workshop. Of these applications, some are unique and highly advantageous. Some are just barely competitive, in our judgments, and some that are no good whatsoever. But they were simply thought through and identified in the process of brainstorming.

That really points the direction for the workshop, because that's what we really have to do. We have to work hard to understand what we really do have, and to highlight the very promising ideas: define them, design them, and make them happen. We must also identify the non-competitive or impractical ideas so that we can reject them.

This is what the workshop is all about. This is why it's a workshop and not simply a symposium where people talk to an audience. We need to get down and do some real work.

If this workshop is successful, we are thinking of having a symposium perhaps a year from now to broaden the audience; but we must do much more before we can really be able to do that.

Thank you for coming this far with us. It's gratifying to see so many fine brains here, and I know you will do a very good job and work hard both here and when you get back to you offices; and, with your work, we can continue to gain credibility and acceptance for tethers and their applications.

Especially, however, we ask your help in weeding out the poor concepts or the marginal applications, because nothing hurts the chances of a new idea as much as being touted as a cure for all ills.

So, thank you for coming. Enjoy the company of your peers. Work hard. I look forward to working with you during these next two days.

Also remember in the process of your work that saying that "Invent a better mousetrap and the world will beat a path to your door." We think that's probably true here except it's probably "Unreel a tether to your spacecraft" rather than "beat a path to your door."

GUEST SPEAKER

James Arnold
California Space Institute

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Thank you. Considering that it is nearly 11 pm, I am reminded of a time when I was at the University of Chicago and was invited to be the after-dinner speaker at a dinner which started not at 9 pm, but at 6:30. There happened to be eleven Chicago municipal judges at the top table. Each of them had to make a few remarks and by the time I got to speak it was about 10:53 pm. About one quarter of the diners were still in the hall -- and you see we started later so we are just steaming up. Of course it is quite a pleasure and honor to be here and most of all because it is an opportunity to share in this event which exists because of a great Italian scientist -- Bepi Columbo.

I can't imagine starting my talk in any other way. I knew him as a planetary scientist for a good many years, but something like three years ago he came to La Jolla to contribute to one of our studies on Shuttle External Tanks. In his typical way that morning he made right away some quite unbelievable statements about external tanks and tethers. As chairman, I asked him to give a little tutorial on tethers after lunch. I am in this hall, and Joe Carroll is in this hall, because of the effect of that tutorial.

I suspect that a fair number of other people here had similar experiences, and that those of you who did not have that direct contact were probably converted by Ivan Bekey or someone else he converted. He would certainly deny that the field of tethers was invented by him.

There were a number of other pioneers before he got into the field. It was in a different sense that he created the field of tethers. The community exists because of him. If it succeeds, the TSS and all related projects will be attributed to him, to a man who not only devised many of the most exciting ideas, but who also persuaded other outstanding scientists and engineers to join him. We can learn just by knowing that there are such wonderful people in the world. Now this field has a life of its own.

I came armed tonight with some documentation on an earlier Italian navigator. As a matter of fact, they had the same name. I never asked Bepi if he was in any way a cousin of the earlier Italian Columbo. I did worry a little bit whether I could talk about this earlier Genoese in Venice, because I remember that there was a certain rivalry between Venice and Genoa. In fact, after his famous triumphs he might have ended up in jail rather than being honored as his merits deserved. However,I was reassured when I examined the document which I will read to you a little bit which is the biography of the gentleman by his son.

Now Venice was, as everyone knows, a center of exploration and a seafaring and trading port. One other distinction, which is very pertinent tonight, is that in the early period after Gutenberg invented printing, Venice was the great center of printing in Europe for many decades, and many important books saw the light first here. And so, although Columbus was a Genoese, and his son Ferdinand by all standards was Spanish, nonetheless the first edition of Ferdinand Columbus' biography of his father was in fact printed in Venice. So I feel safe in quoting from his book.

I don't quite remember who first called my attention to this biography. But if you are an American, as some of you are, you learn about Columbus in school in a haze of myth. You have the feeling that he was somebody so dim in history that it would be almost ludicrous that he could have a son who was an author. But it turns out that he is one of the best documented characters in history. Spanish records, which are very full, contain thousands of letters, charters, and so on.

I used to read passages from Ferdinand Columbus' book about his father in connection with struggles to mount a mission called the Lunar Polar Orbiter, which we are still struggling to get started. I think that these quotations are also appropriate on this occasion, and not only because of the coincidence in names between our Columbo and that Columbo. I think it will not be difficult for some of you to recognize some of the trials the earlier Columbo went through as similar to the tribulations of the newer man and his friends. Ferdinand describes his father's efforts to sell his plans to various nations. Portugal and Spain were the United States and Soviet Union of that particular period of history. At any rate, he tried first in Portugal to persuade the King of Portugal to send a craft to discover the New World, but that didn't work. He sent his brother to England, and he was corresponding with the King of France. He knew the rule: don't put all your eggs in one basket. In Spain, when Portugal said no, he made contact with some influential persons to get to others. Finally after a whole series of adventures, he penetrated the Spanish establishment, and got the leading friar (of course the clergy and the scholars were all one group in those days), to undertake his cause in the court of Spain. My first quotation from this book describes this particular period, about 1491, when he was

trying to get his grant approved. And the text goes like this -- I'm skipping a little:

"But since the affair had more to do with basic scientific doctrine than with words or favors, their Highnesses referred it to the Prior del Prado, later the Archbishop of Granada, ordering him to form a council of geographers who should study the proposal in detail and then report to them their opinion." This is called peer review today.

"As there were not so many geographers then as now, the members of this committee were not so well informed as the business required. Nor did the Admiral wish to reveal all the details of his plan, fearing lest it be stolen from him in Castile as it had been in Portugal. For this reason the replies and reports that the geographers gave their Highnesses were as varied as their grasp of the subject and their opinions. Some argued in this way: In all the thousands of years since God created the world, those lands had remained unknown to innumerable learned men and experts in navigation; and it was most unlikely that the Admiral should know more than all other men, past and present. Others who based themselves on geography, claimed the world was so large that to reach the end of Asia, where the Admiral wished to sail, would take more than three years." (There is a footnote here: in fact my friend Carl Sagan pointed out to me that if there wasn't a North American and South American continent in the way Columbus could not have carried enough provisions on the ship to reach Japan and return. There was indeed risk, but there were benefits.) And then he goes on to quote the other authorities, "Others argued as some Portuguese had done about the navigation to Guinea, saying that if one were to set out and travel due

west, as the Admiral proposed, one would not be able to return to Spain because the world was round. These men were absolutely certain that one who left the hemisphere known to Ptolemy would be going downhill and so could not return; for that would be like sailing a ship to the top of a mountain: a thing that ships could not do even with the aid of the strongest wind.

"The Admiral gave suitable replies to all these objections, but the more effective his arguments, the less these men understood on account of their ignorance: for when a man poorly trained in mathematics reaches an advanced age, he is no longer capable of apprehending the truth because of the erroneous notions previously imprinted on his mind." Some of us have had such experiences. And then he goes on -- let me skip to a later part of the story -- because of course Columbus succeeded. He had driven a bargain with the monarchs of Spain, Ferdinand and Isabella, and so he was adorned with titles and promises of money, not real money, promises of money. He was of course the great sensation of the European courts -- for a period of many years this was the most exciting thing that had happened and there was an enormous PR success. But there were problems. Ferdinand and Isabella had financed this expedition with the expectations of cash. They expected a quick payoff from Columbus's discoveries.

I will read to you now something that Ferdinand told from his own point of view, as a son of a suddenly high member of the Spanish nobility. Here he describes a scene ten years later, when he was a teenager, a page in the court of Spain.

"With these and similar calumnies they importuned the Catholic Sovereigns, complaining that the Spaniards had not received true value for their contributions for many years past, etc. I remember that when I was at Granada, more than fifty of these shameless wretches bought a quantity of grapes and sat down to eat them in the Court of the Alhambra loudly proclaiming that their Highnesses and the Admiral had reduced them to that pitiful state by withholding their pay, adding many other insolent remarks. They were so shameless that if the Catholic King rode out, they would crowd about him, shouting, 'Pay, pay!' and if my brother and I, who were pages to the Queen, happened by, they followed us crying, 'There go the sons of the Admiral of the Mosquitoes, of him who discovered lands of vanity and illusion, the grave and ruin of Castilian gentlemen,' adding so many other insults that we took care not to pass before them."

Now some of us in America have heard this kind of talk too. Twenty-five years after Sputnik, and fifteen years after the landing on the moon, there are the occasional Congressional figures or newspaper columnists who use language pretty similar to language used here. But the most pointed quotation is the one which I will use as the text (as the preacher says) for the rest of my sermon. This is this last one.

When the Spanish sovereigns were faced with the fact that Columbus had succeeded in making a great discovery they didn't quite know how to deal with it. The general recipe was that as soon as he got back from the Americas with a new collection of discoveries -- islands named Isabella and Ferdinand for example -- they would propose another expedition and send him back to the new world again. As long as he was in the new world, he wasn't in their hair. This went on and on. Naturally Columbus, who thought he had done something remarkable, became frustrated by this treatment. The son describes a letter the Sovereigns wrote to Columbus, just after the third expedition, suggesting a fourth expedition. Then he says, "The Sovereigns made these promises and offers to the Admiral because he had resolved to have nothing more to do with the affairs of the Indies and to turn them over to my brother, concerning which he reasoned well. For, said he, if the services he had already performed did not suffice to secure the punishment of those wicked men, his future services would avail even less. He had already accomplished the main thing that he had offered to do before his discovery of the Indies, namely, to show that there were islands and a continent to the west, that the way thither was easy and navigable, the advantages plain, and the inhabitants very gentle and unarmed." I can't refrain from repeating that last phrase, "the inhabitants very gentle and unarmed." "And since he had personally verified all this, it remained only for their Highnesses to continue what he had begun, sending out people to discover the secrets of those countries. Now the gate was open, anyone could follow the coast, as some were already doing who improperly called themselves discoverers, not considering that they had not discovered any new land, but only followed in the wake of the Admiral after he had shown them the way to those islands."

I may remark that I come from a continent called America not Columbia, and if you think about history a little bit it shows that this remark is very much to the point. Amerigo Vespucci was a Florentine, but we are not in Florence. "However, since the Admiral had always had a great desire to serve the Catholic Sovereigns and especially the most serene Queen, he was content to return to his labors and make the voyage to be told of hereafter. For he was convinced that new treasures would be found daily, as he had earlier written to their Highnesses in reference to the discovery: 'It must be followed up, because it is certain if not now, then later some new thing of great value will be found.'" The son ends his remarks, "Mexico and Peru have since shown the truth of this observation, but at the time nobody believed what he said. Yet he said nothing that did not prove in time to be true."

We are just now coming out of a parallel period. At least I believe so. We have gone through a time when space was the most exciting thing that anybody could have envisioned. We have watched Apollo's television ratings drop. The budgets dropped as the ratings dropped. Real dollars for civilian space in the United States are now only approximately 1/3 the original budgets of 1968. I believe the period we are just now entering will be parallel to the experience of Cortez and Pizarro, with a single remarkable, and to my mind a very pleasant exception. We will not be doing it out of the blood and sweat of inhabitants who are very gentle and unarmed, but out of technology and the intelligence which we ourselves apply to the problem. I think that this is a stage in history where the second takeoff is on the way, and I believe (as you do or you would not be attending the conference) that tethers are one of the paths to the future.

The technology of today is the key to the state we are in. We have got to where we are in the exploration of the solar system and astronomical satellites in earth orbit, the whole range of space activities, using the tools developed by Werner von Braun and his contemporaries.

Von Braun in the early 1930's joined a small German club called the Verein für Raumschiffahrt. He then began using the German government and then the American government to accomplish his own goals, to go into space. That technology, it appears to me, has now matured. While incremental advantages can always be expected you still need 80 tons of rocket fuel to lift one ton of useful payload to low earth orbit. In the future that may come down to 70 tons or 60 tons or 50 tons. But still because of the deep gravitational well we find ourselves in, we have reached some kind of maturity in the Columbus-stage of our exploration.

If we want to have a second stage we have to be smart. This conference is about that and tethers are surely the most prominent of the next wave of promising technologies. I think it would not be a complete waste of time, even this late in the evening, to say that this is not the only promising technology around. While I don't know one better than tethers, as one penetrates into space one finds what Enrico Fermi found in high energy physics, that phenomena and possibilities open up that you would never imagine at the start. More and more new things appear.

Let me read my own personal list: Ion engines -- they have been around for a long time. Right now, just as Italy is pushing tethers, the Germans are pushing ion engines and I am delighted that is true. This is in a way an old idea which has been proposed in many varieties. There are a whole range of electromagnetic launching schemes; this is only one. Rockets are chemistry, and I am a chemist. I think I understand this subject. There is a limit with what you can do with chemistry

-- you can get a few electron volts per atom at most. Electromagnetic induction -- here you get into devices not so well developed as tethers, devices called railguns, devices called mass drivers, devices recently named coil guns. I think that these things may have some prospect of actually launching useful payloads from the earth. Tethers aren't very close to doing this, up to now. There are good prospects of launching payloads from the moon. Solar sails -- these have been around for a while. What's so exciting to me about solar sails is that this project has been carried on by amateurs. Some of the highest priced talent in the world is working for free Saturdays and Sundays to develop solar sails to a practical level. You've seen in the case of Gossamer technology on earth that this can be successful.

Ivan is sitting here waiting for me to mention External Tanks. Let me add to the External Tank story, something closely related to it. My phrase is: external tanks and other forms of space salvage. External tanks have uses beyond the space junk business, but the space junk business may turn out to be a real winner for some people even if the title lacks glamor. We have the problem of thousands of orbiting objects threatening the tethers which we want to use in low earth orbit. What a great idea it would be to retrieve them using tethers as fishlines. Lunar Resources -- a little further down the road this will surely be important.

The United States now has a Presidential Commission looking at 21st century plans. People are looking at manned missions to Mars, and all sorts of giant steps. One need not lift huge things from the deep well of the earth. In the case of the moon, the energy required to lift objects into orbit is only a few percent of what it is on the earth. No one will be surprised to learn that Joe Carroll has ideas for lifting lunar materials from the surface using tethers. And if we give Joe a little more time to find materials with a higher strength to weight ratio, he may sling these things right off the earth for all I know.

Beyond all these things there are the moons of Mars, asteroids, and who knows what. Christopher Columbus did not in fact become rich doing what he did. If one could revisit the fifteenth century and ask him if it mattered very much, I suppose he would say it did not. However, his son, who undertook to write his biography, was prosperous enough to build one of the best scholarly libraries in Europe. Cortez and many others, who made few discoveries, became wealthy beyond their dreams. And if money is to be made in space, it will not perhaps be the Columbos who become rich either. At the California Space Institute, we have a term for this part of our activities -- space manufacturing -- and to be frank about it that is what I would call a code word. If you want to persuade practical people to do something useful you have to use modest terms. But in reality, I myself believe the game is much larger than that.

I got into it first because I was a planetary scientist and wanted to go back to the moon and study and continue the adventure which had begun with Apollo and Viking, the exploration of the moon and planets. But I have come to realize that there is much more to it. What we are talking about, if the tether experts here really succeed, and if other technologies begin to develop, is not a way of making chips in space so that the Silicon Valley people can make more money, or somebody else can put the Silicon Valley people out of business -- those will be incidents of the early life of the project. What we are really talking about is the movement of humanity, and the variety of earthly life which we represent, into space. We are talking about settling the solar system, about a vista so long that, in a phrase I used in an earlier talk, we can speak of our descendants of whatever species. Human beings, once they are on the moon, once they are on Mars, once they go around Jupiter on various satellites, will not be the same as they are now. That will be a fairly decisive change, one which will make the first Columbo explorations look relatively small.

I don't think the twentieth century has been very benign. Like the fifteenth century which produced Columbus, like the centuries which produced other great human triumphs, it has been a pretty bleak, a pretty brutal century. I sometimes think there is an association between the two -- creativity and inhumanity. All the same, if in fact we are taking part in a revolution which brings humanity into a new sphere, then I think our descendants, whether they are still Homo sapiens or something we cannot now imagine, will remember that we have not lived in vain. That is a goal, I believe, worthy of Bepi Columbo, and of our own best endeavors. Thank you.

GENERAL PRESENTATIONS

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TETHERED SATELLITE SYSTEM

James Sisson
Marshall Space Flight Center, NASA

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N86-28408

Thank you, Professor Guerriero.

Ivan, you mentioned the sometimes rather derisive remarks people make to you regarding tethers. When they make them to us, they ask how the tether is going, and we tell them we're hanging in there.

If you cannot see these charts clearly, they will be in the proceedings of the workshop and, in fact, the charts that I will submit for the workshop will go into more detail. We had to trim our presentation down. Also, if there are any questions, I'd be happy to answer those at any time during the proceedings.

If you don't mind, I'll look here and address the viewgraph rather than turn my back on you.

(Chart 1) The objective of the tethered satellite -- the TSS-1 -- is to develop the hardware, both on the satellite and a deployer side, for either a 20-kilometer or 100-kilometer deployment of the tether, either away from or toward the Earth. As you see, there are a variety of scientific interests; magnetometry, electrodynamics, and atmospheric science are of great interest.

(Charts 2-4) And I think, as has been discussed this morning, that the endeavor between the Italian government and the United States government in a joint development is very important. I'm not going to bore you with a detailed organization chart — but I think it's very important for you to understand the relationship between the National Aeronautics and Space Administration and Italy's PSN/CNR organization in carrying out this program.

On the left, you see the responsibility of the United States and NASA in the development of the deployer, which fits in the orbiter cargo bay, and the integration of the satellite to the deployer and the conduct of the mission.

On the right, you see the responsibility of the Italian government, leading down to the contractors on both sides in this very important endeavor. On the United States side is Martin-Marietta Aerospace at Denver, which is responsible for hardware and integration for the United States′ responsibilities. On the Italian side is Aeritalia, who is developing and designing the satellite.

Along with that are the scientific responsibilities between the two countries. All of the European science investigations are the responsiblity of PSN and Aeritalia. And, on the United States side, are all non-European scientific investigations, the development of those instruments, and also the integration of all instruments on the deployer.

So the only reason I show this is to emphasize the very important relationships between the two countries.

(Chart 5) A few words about the first mission. The first mission is an engineering verification and electrodynamics science mission. That is, we must certainly prove without a doubt that we can deploy and retrieve a satellite safely. The first mission will be a 20-kilometer upward deployment with a conducting tether to demonstrate the electrodynamics science.

I will show you the timeline in a few moments. It′s nominally a 38-hour mission at a 160 nautical mile Shuttle orbit.

The deployer design for all missions is to be able to fly a conducting or non-conducting tether up to a hundred kilometers. We have a full length boom of 12-meters to extend the satellite out away from the deployer prior to deployment.

The satellite itself is a 1.6 meter, 500-kilogram satellite, with lateral and in-line tether satellite thrusters, to maintain control at the close-in distances. That is the first TSS flight on which we are proceeding.

(Chart 6) This is the configuration that is under development at this point in time. This is the forward direction in flight. We have the basic Spacelab pallet with the deployer and satellite mounted on the pallet. We have a structure called the Mission Peculiar Equipment Support Structure (MPESS), which is nothing more than a structure to support scientific payloads. The advantage of this is to be able to put most of the scientific instruments on a separate structure from the deployer to simplify reflight. It makes a much simpler integration job.

(Chart 13) For those who may be interested in the configuration of the tether that we have to date — this may not be the final flight configuration, but it's very close to it.

The tether itself has a Nomex core around which is wrapped a copper conductor equivalent to a 24-gauge conductor, with an insulator wrapped around that. And then the load-carrying member is Kevlar 29. It has about a 400-lb. strength capability. And then around that is woven a Nomex jacket to protect against monatomic oxygen effects, which we have noticed on past Shuttle flights.

The diameter is about two millimeters. On the first mission, since only 20 kilometers are reeled out, the loads on the tether itself will be very small.

If you would care to look at this after the session or any time this week, I would be happy to show it to you.

(Chart 14) I won't go into this in a lot of detail because I don't know a lot of the details about it. The thing I wanted to point out is, I personally came into the project with people telling me it's a very simple, straightforward easy-to-accomplish, inexpensive project. The more we get into it, the more complex it is. I had one individual tell me that the communication links between a deployed satellite with which you still have control, the orbiter, its communications system, the enhanced pallet, which has a computer system on the pallet that talks to the deployer as well as the pallet, as well as the scientific instru-

ments, the communications links -- oh, pardon me -- and the S-band communication link, the Ku-band man tracking it all the time; he felt the communication loops between tether were more complex than Spacelab 1. And Spacelab 1 was very complex.

We have a lot of organizational interfaces, and anytime one has organizational interfaces, trying to build a payload or fly a mission, it's very complex, and the communication between us must always be very clear. That's one of our -- I think -- our greater challenges.

So we have the orbiter with the pallet. We will use the Marshall Space Flight Center -- Payload Operations Control Center -- as well as the Johnson Mission Control Center. Johnson will be responsible and have control of the total mission.

This is the data display control unit. That is what is called the DDCU computer for what I'll call it the SMART pallet. We will do some science processing with that.

And these items here on the flight deck, which will be under control of the Payload Mission specialists.

So I think the communication loops are very complex.

(Chart 15) As I said, for the mission operations, we will have use of the Huntsville Operations Support Center, which will do the engineering support for the deployer, and the Spacelab pallet. It is the engineering support to Houston which will conduct the mission. We will use the Payload Operations Control Center at Marshall to do the scientific support. We will also use, that is, plan on using, the Payload Crew Training Complex, which was used on the Spacelab missions for training the onboard crew for operations.

We have recently established a Flight Operations Working Group to start that endeavor. And we are just beginning to get fairly deep into the integration of JSC on the conduct of the mission and the payload operations functions.

(Chart 16) I'll say a little bit about the timeline for the total 38 hours. This has been modified, or probably will be modified, somewhat. We had the second investigators working group meeting in Italy last week, and they had some recommendations that change the timeline.

But, in essence, the deployment will take about ten hours, the reason being, at this point in the baseline, that we have two stops. We would like to deploy out to about ten kilometers, stop, spin the satellite up, take science data for about an hour and a half, and then de-spin it. And then go on to station at 20 kilometers for about 18 to 20 hours.

I show a crew sleep cycle there, although I don't really believe that will ever happen. I can't imagine a satellite being deployed out on the station and people sleeping with the satellite out, but that's in the timeline.

For planning purposes, I think that's a good idea, because we should, I believe, baseline ourselves such that we can control the science from the ground during that time period with the crew in the monitoring mode. I believe that's the way they will end up with it.

And then, at the end of that 31 hours total, would be a retrieval. At this point in time, we see no reason to stop on the way back in. It would take away from the time on-station, so our plan right now is to start the retrieval and pull it straight on in at the end of the 38 hours.

(Chart 17) I'll say a few words about the science that has been selected, and then just leave it at that.

The science is split between the satellite, that is the science that goes on the satellite, and that which goes on the deployer. Marino Dobrowolny has been selected to do the electrodynamic tether effects, Dr. Nobie Stone at Marshall Space Flight Center on the satellite, and Professor Mariani at the University of Rome with the magnetic fields. This is orbiter instrumentation. That's really science instruments that go on the deployer. Peter Banks at Stanford with his experiment. That has been changed to Drobot, I believe, on the plasma coupling studies. Gullahorn at the SAO, and Bergamaschi at Padua, and Bob Estes on the electronic emissions.

That's all the charts I had. The status we're in right now; we're coming up on a critical design review for the deployer in about a month. In fact, it's already started. And that means that we have about 90 percent of the design complete on the deployer.

And we are into the first parts of structures manufacturing, so we are in a position now of cutting hardware for this.

The first flight is scheduled for September 1988 -- and that may seem a long time away, but it will be here before we know it.

Thank you very much.

2970—85

TETHERED SATELLITE SYSTEM

PROJECT OVERVIEW

TETHERED SATELLITE SYSTEM
A COOPERATIVE PROJECT-USA & ITALY
NASA-CNR

APPLICATIONS OF TETHERS IN SPACE WORKSHOP
VENICE, ITALY
OCTOBER 15–17, 1985

JAMES M. SISSON
NASA/MSFC

ORGANIZATION: FA31	MARSHALL SPACE FLIGHT CENTER	NAME: J. SISSON
CHART NO. 3546—85	TETHERED SATELLITE SYSTEM	DATE: OCTOBER 1985

OBJECTIVES

● SYSTEMS

DEVELOP A REUSABLE SYSTEM TO ENABLE A VARIETY OF SCIENTIFIC INVESTIGATIONS TO BE ACCOMPLISHED FROM THE SHUTTLE, CONSIDERING:

- USE OF A TETHERED SYSTEM WITH MANUAL/AUTOMATED CONTROL
- DEPLOYMENT OF A SATELLITE TOWARD OR AWAY FROM THE EARTH, UP TO 100 KM
- CONDUCTING OR NON—CONDUCTING TETHER

● SCIENTIFIC

PERFORM EXPERIMENTS AND SCIENTIFIC INVESTIGATIONS USING THE TETHER SYSTEM FOR APPLICATIONS SUCH AS:

- MAGNETOMETRY
- ELECTRODYNAMICS
- ATMOSPHERIC SCIENCE
- CHEMICAL RELEASE
- OTHER

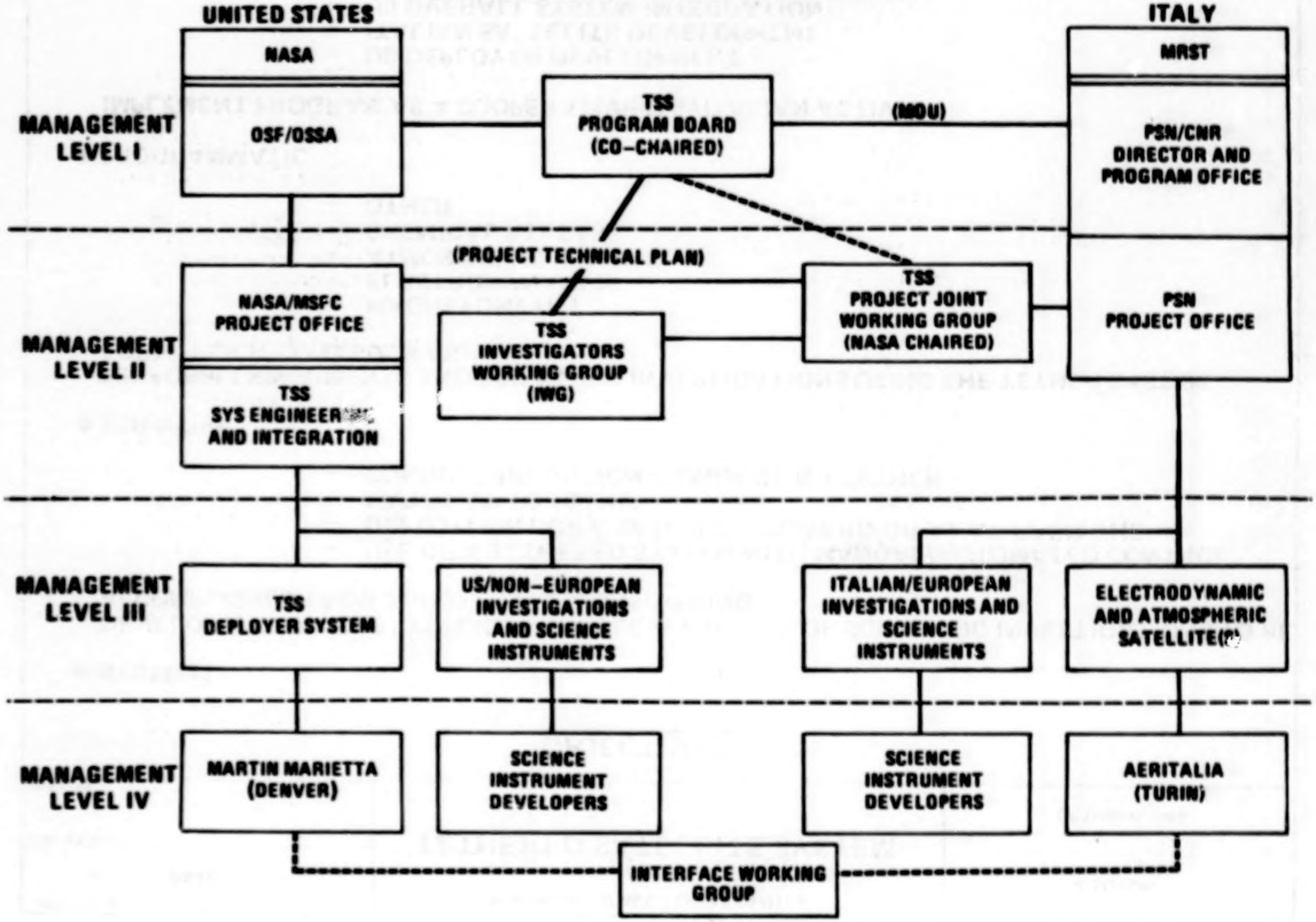
● PROGRAMMATIC

IMPLEMENT PROGRAM AS A COOPERATIVE U.S./ITALIAN ACTIVITY

- US DEPLOYER DEVELOPMENT
- ITALIAN SATELLITE DEVELOPMENT
- US OVERALL SYSTEM INTEGRATION
- JOINT US/ITALIAN SCIENCE DEVELOPMENT/INTEGRATION

1988—84 (REV D)

TETHERED SATELLITE SYSTEM MANAGEMENT RELATIONSHIPS


UNITED STATES
ITALY
MANAGEMENT LEVEL I
NASA
OSF/OSSA
TSS PROGRAM BOARD (CO–CHAIRED)
(MOU)
MRST
PSN/CNR DIRECTOR AND PROGRAM OFFICE
MANAGEMENT LEVEL II
(PROJECT TECHNICAL PLAN)
NASA/MSFC PROJECT OFFICE
TSS SYS ENGINEERING AND INTEGRATION
TSS INVESTIGATORS WORKING GROUP (IWG)
TSS PROJECT JOINT WORKING GROUP (NASA CHAIRED)
PSN PROJECT OFFICE
MANAGEMENT LEVEL III
TSS DEPLOYER SYSTEM
US/NON–EUROPEAN INVESTIGATIONS AND SCIENCE INSTRUMENTS
ITALIAN/EUROPEAN INVESTIGATIONS AND SCIENCE INSTRUMENTS
ELECTRODYNAMIC AND ATMOSPHERIC SATELLITE(?)
MANAGEMENT LEVEL IV
MARTIN MARIETTA (DENVER)
SCIENCE INSTRUMENT DEVELOPERS
SCIENCE INSTRUMENT DEVELOPERS
AERITALIA (TURIN)
INTERFACE WORKING GROUP

ORGANIZATION: TSS PROJECT OFFICE	MARSHALL SPACE FLIGHT CENTER **TETHERED SATELLITE SYSTEM PROJECT OVERVIEW**	NAME: J. SISSON
CHART NO. 2874–85		DATE: OCTOBER 1985

TSS PROGRAM RESPONSIBILITIES

UNITED STATES

NASA HEADQUARTERS

- PROGRAM MANAGER (OSF)
- PROGRAM SCIENTIST (OSSA)

TSS PROJECT OFFICE

- PROJECT MANAGER
- MISSION MANAGER
- TSS SYSTEM ENGINEERING & INTEGRATION
- TSS DEPLOYER/SYSTEM DEVELOPMENT
- CHANGE CONTROL BOARD, LEVEL II, III
- CONTRACT MANAGEMENT/EVALUATION
- LAUNCH/MISSION OPS. PLANNING/SUPPORT
- SCIENCE INSTRUMENT DEVELOPMENT
- CORE EQUIPMENT DEVELOPMENT
- SCIENCE/CORE EQUIPMENT INTEGRATION

MARTIN MARIETTA AEROSPACE

- OVERALL SE&I SUPPORT/IMPLEMENTATION
- DEPLOYER SYSTEM DEVELOPMENT
- EXPERIMENT DEVELOPMENT/INTEGRATION
- LAUNCH/MISSION OPERATIONS SUPPORT

ITALY

NATIONAL RESEARCH COUNCIL (CNR)
NATIONAL SPACE PLAN (PSN)

- PROGRAM/PROJECT MANAGER
- PROGRAM/PROJECT SCIENTIST
- TSS SATELLITE DEVELOPMENT
- SCIENCE INSTRUMENT DEVELOPMENT
- CORE EQUIPMENT DEVELOPMENT
- SATELLITE SCIENCE/CORE INTEG.
- GROUND/FLIGHT OPS. SUPPORT
- LAUNCH/MISSIONS OPS. SUPPORT

AERITALIA, SUB–CONTRACTORS

- SATELLITE SYSTEM DEVELOPMENT
- EXPERIMENT DEVELOPMENT/INTEG.
- LAUNCH/MISSION OPS. SUPPORT

ORGANIZATION:
TSS PROJECT OFFICE

CHART NO.:
2975–86

MARSHALL SPACE FLIGHT CENTER

TETHERED SATELLITE SYSTEM
PROJECT OVERVIEW

NAME
J. SISSON

DATE.
OCTOBER 1986

TSS PROGRAM RESPONSIBILITIES, UNITED STATES (CONT'D)

MARSHALL SPACE FLIGHT CENTER

SCIENCE & ENGINEERING

- PROJECT ENGINEER
- PROJECT SCIENTIST
- LABORATORY DISCIPLINE SUPPORT
  - COUPLED DYNAMICS, LOADS
  - FRACTURE MECHANICS, MUA'S
  - EEE PARTS, ETC. ETC.
- DYNAMICS WORKING GROUP
- C&DH WORKING GROUP
- HOSC, MSFC POCC, PCTC
- FLIGHT OPERATIONS WORKING GROUP
- GROUND OPERATIONS WORKING GROUP
- DESIGN REVIEW SUPPORT
- PERFORMANCE EVALUATION SUPPORT

SPACELAB PROGRAM OFFICE

- A & B LEVEL ICD
- ENHANCED MDM PALLET, MPESS
- ENGINEERING MODEL PALLET
- THERMAL ANALYSIS AND DESIGN
- STD. & SPECIAL COLDPLATES
- UTILITIES

SAFETY OFFICE

- SYSTEM SAFETY

ADMINISTRATION & PROGRAM SUPPORT

- PROCUREMENT
- PERSONNEL, OTHER

OTHER CENTERS

JOHNSON SPACE CENTER

- FLIGHT OPERATIONS
- CREW TRAINING
- PAYLOAD INTEGRATION PLAN
- SHUTTLE ENGINEERING SIMULATOR
- FLT. OPS. SAFETY REVIEW BOARD
- FLIGHT DATA FILE

KENNEDY SPACE CENTER

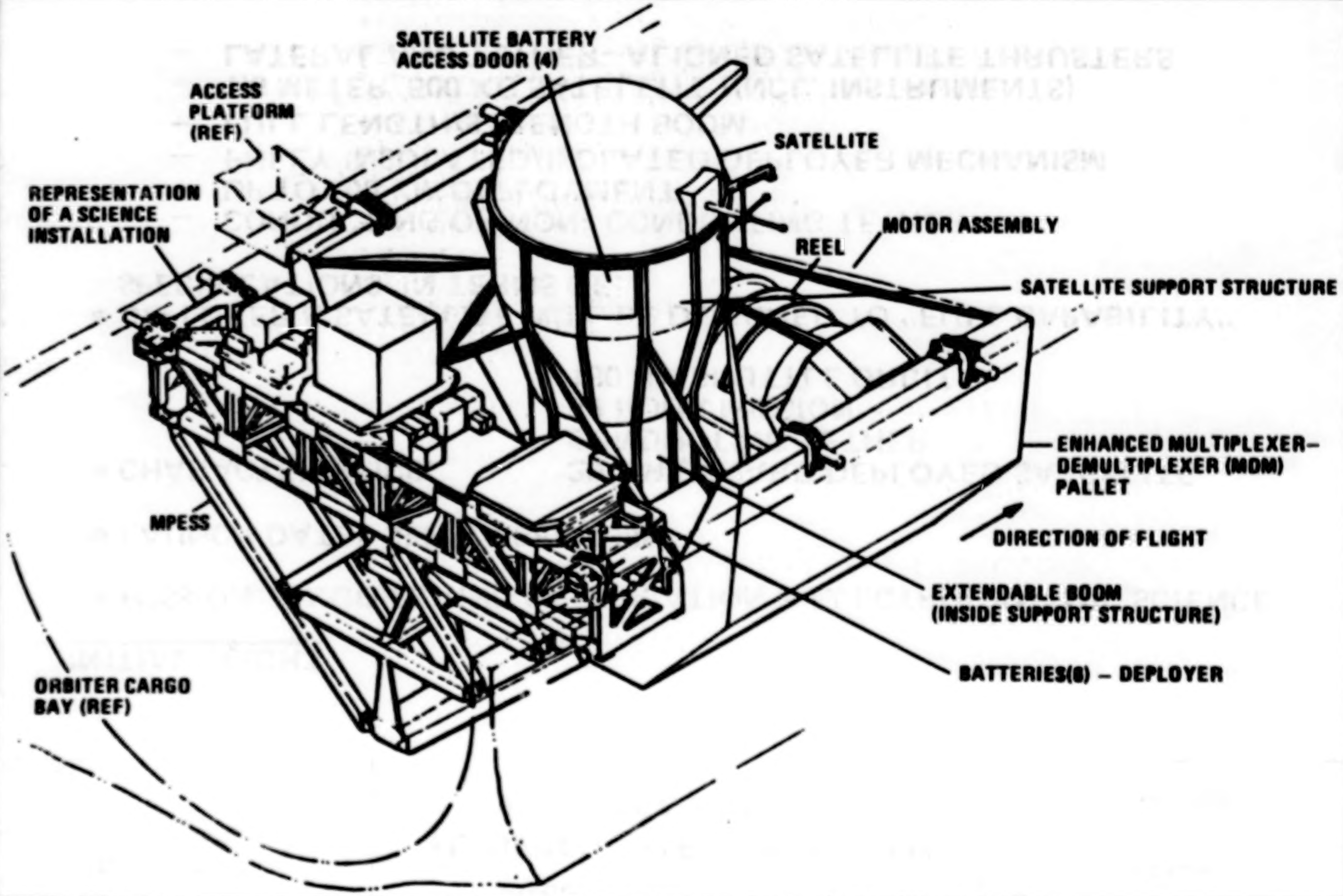
- LEVEL IV INTEGRATION
- ASSEMBLY & END–TO–END TESTS
- GROUND/LAUNCH OPERATIONS
- DEINTEGRATION, PAD CHANGE–OUT
- GROUND OPS. SAFETY REVIEW BOARD

ORGANIZATION: TSS PROJECT OFFICE	MARSHALL SPACE FLIGHT CENTER **TETHERED SATELLITE SYSTEM PROJECT OVERVIEW**	NAME: J. SISSON
CHART NO.: 2973-85		DATE: OCTOBER 1985

INITIAL FLIGHT

- **MISSION: ENGINEERING VERIFICATION & ELECTRODYNAMIC SCIENCE**
- **LAUNCH DATE: SEPTEMBER 1988**
- **CHARACTERISTICS:**
  - 20 KM UPWARD DEPLOYED SATELLITE
  - CONDUCTING TETHER
  - 38 HOUR MISSION
  - 160 NM SHUTTLE ORBIT
- **DEPLOYER & SATELLITE WILL BE DESIGNED TO "FULL CAPABILITY" SPECIFICATIONS, IN TERMS OF:**
  - CONDUCTING OR NON–CONDUCTING TETHER
  - UP TO 100 KM DEPLOYMENT
  - FULLY INSULATED/ISOLATED DEPLOYER MECHANISM
  - FULL LENGTH/STRENGTH BOOM
  - 1.6 METER, 500 KG SATELLITE (INCL. INSTRUMENTS)
  - LATERAL AND TETHER–ALIGNED SATELLITE THRUSTERS

ORGANIZATION: FA31	MARSHALL SPACE FLIGHT CENTER **TETHERED SATELLITE SYSTEM MISSION 1 CONFIGURATION**	NAME: JAMES M. SISSON
CHART NO.: 3548–85		DATE: OCTOBER 1985


SATELLITE BATTERY ACCESS DOOR (4)
ACCESS PLATFORM (REF)
SATELLITE
REPRESENTATION OF A SCIENCE INSTALLATION
MOTOR ASSEMBLY
REEL
SATELLITE SUPPORT STRUCTURE
ENHANCED MULTIPLEXER–DEMULTIPLEXER (MDM) PALLET
MPESS
DIRECTION OF FLIGHT
EXTENDABLE BOOM (INSIDE SUPPORT STRUCTURE)
BATTERIES(6) – DEPLOYER
ORBITER CARGO BAY (REF)

ORGANIZATION: FA31
CHART NO.: 3549-85

MARSHALL SPACE FLIGHT CENTER

TETHERED SATELLITE SYSTEM MAJOR ELEMENTS/CAPABILITY

NAME: JAMES M. SISSON
DATE: OCTOBER 1985

- ● SPACE TRANSPORTATION SYSTEM (STS)
  - LAUNCH/ON–ORBIT PLATFORM/LANDING
  - UPLINK COMMAND/DOWN LINK DATA/CREW COMMUNICATIONS
  - 28.5 DEGREE INCLINATION
  - –Z LOCAL VERTICAL ATTITUDE (TSS OPERATIONS)
  - 297 KILOMETER ALTITUDE (NEAR CIRCULAR ORBIT)
  - KU–BAND RADAR TRACKING OF SATELLITE
- ● ENHANCED MULTIPLEXER–DEMULTIPLEXER (MDM) PALLET
  - STRUCTURAL
    - ● HARD POINT MOUNTS
    - ● EQUIPMENT MOUNTING PANELS
  - ELECTRICAL
    - ● MAIN BUS
    - ● AUXILIARY BUS
    - ● POWER DISTRIBUTION/CONTROL
  - THERMAL
    - ● FREON COOLANT LOOP
    - ● COLD PLATES
  - COMMAND AND DATA MANAGEMENT
    - ● UPLINK COMMAND PROCESSING
    - ● DATA MULTIPLEXING INTERFACE TO STS
    - ● DATA DISPLAY AND CONTROL UNIT (DDCU)
    - ● SPECIAL DATA PROCESSING

ORGANIZATION: FA31	MARSHALL SPACE FLIGHT CENTER	NAME: JAMES M. SISSON
CHART NO.: 3650–85	**TETHERED SATELLITE SYSTEM MAJOR ELEMENTS/CAPABILITY**	DATE: OCTOBER 1985

- **MISSION PECULIAR EQUIPMENT SUPPORT STRUCTURE (MPESS)**
  - – STRUCTURAL
    - ● SCIENCE
    - ● DEPLOYER BATTERIES
  - – ELECTRICAL
    - ● RECEIVE POWER FROM PALLET
    - ● DISTRIBUTE POWER TO SCIENCE
    - ● ROUTE DEPLOYER BATTERY POWER TO PALLET
  - – THERMAL
    - ● FREON LOOP INTERFACE TO PALLET
    - ● COLD PLATES
  - – COMMAND AND DATA MANAGEMENT
    - ● ROUTE COMMANDS TO SCIENCE
    - ● ROUTE DATA FROM SCIENCE/DEPLOYER BATTERIES

ORGANIZATION: FA31	MARSHALL SPACE FLIGHT CENTER	NAME: JAMES M. SISSON
CHART NO.: 3554-85	**TETHERED SATELLITE SYSTEM MAJOR ELEMENTS/CAPABILITY**	DATE: OCTOBER 1985

- DEPLOYER
  - REEL/MOTOR ASSEMBLY
    - REEL CAPACITY
      - 20 KILOMETERS (CONDUCTING TETHER)
      - 100 KILOMETERS (NON–CONDUCTING TETHER)
    - REEL MOTOR TORQUE – ± 54.5 NEWTON–METERS (~ 40 FT–LBS)
    - REEL MECHANICAL BRAKE
    - REEL ELECTRO–MECHANICAL BRAKE (MOTOR–GENERATOR/LOAD BANK)
    - LEVEL WIND DEVICE
    - REEL SPEED – 0 TO 600 RPM
    - CONTROLLED BY MOTOR CONTROL ASSEMBLY
    - ELECTRICALLY ISOLATED INTERFACE TO TETHER CONDUCTOR
  - DATA ACQUISITION AND CONTROL ASSEMBLY
    - ACCEPT/PROCESS UPLINK COMMANDS (2 KBPS)
      - DEPLOYER
      - ATTACHED SATELLITE
    - COLLECT/MULTIPLEX DOWN LINK DATA (16 KBPS)
      - DEPLOYER
      - ATTACHED SATELLITE

ORGANIZATION: FA31

CHART NO.: 3866–85

MARSHALL SPACE FLIGHT CENTER

TETHERED SATELLITE SYSTEM MAJOR ELEMENTS/CAPABILITY

NAME: JAMES M. SISSON

DATE: OCTOBER 1985

- DEPLOYER (CONTINUED)
  - DATA ACQUISITION AND CONTROL ASSEMBLY (CONTINUED)
    - CONTROL TETHER DURING DEPLOY/RETREIVE/ON STATION
      - SOFTWARE CONTROLLED
      - ALGORITHMS
      - DEPLOYER SENSORS
      - INTERMEDIATE STOP CAPABILITY
    - CONTROL/MONITOR BOOM EXTEND/RETRACT
  - SATELLITE SUPPORT STRUCTURE
    - SUPPORT 500 KILOGRAM SATELLITE
    - SATELLITE ROTATION ± 185^{o}
    - SATELLITE ALIGNMENT GUIDE
    - 6 SATELLITE LATCHES
    - CONTAINS BOOM
    - 2 SATELLITE UMBILICALS (NON–RECONNECTABLE)
      - 1 SEPARATES AT 60 CM BOOM MOVEMENT
      - 1 SEPARATES AT FULL BOOM EXTENSION
    - SPRINGS/GUIDE RAILS FOR BOOM JETTISON
    - BOOM EJECTION PYROTECHNICS

ORGANIZATION: FA31	MARSHALL SPACE FLIGHT CENTER **TETHERED SATELLITE SYSTEM MAJOR ELEMENTS/CAPABILITY**	NAME: JAMES M. SISSON
CHART NO.: [illegible]-85		DATE: OCTOBER 1985

- DEPLOYER (CONTINUED)
  - TETHER CONTROL
    - TENSION (INBOARD) – 0 TO 100 NEWTONS (EDM)
– 0 TO 400 NEWTONS (ATM)
    - TENSION (OUTBOARD)– 0 TO 15 NEWTONS
    - LENGTH MEASUREMENT – 0 TO 22 KILOMETERS
    - RATE – +12 METERS/SEC TO – 12 METERS/SEC
    - UPPER TETHER CONTROL MECHANISM (TOP OF BOOM)
    - LOWER TETHER CONTROL MECHANISM (BOTTOM OF BOOM)
    - UPPER TETHER CUTTER
    - LOWER TETHER CUTTER

ORGANIZATION: FA31
CHART NO.: [illegible]

MARSHALL SPACE FLIGHT CENTER

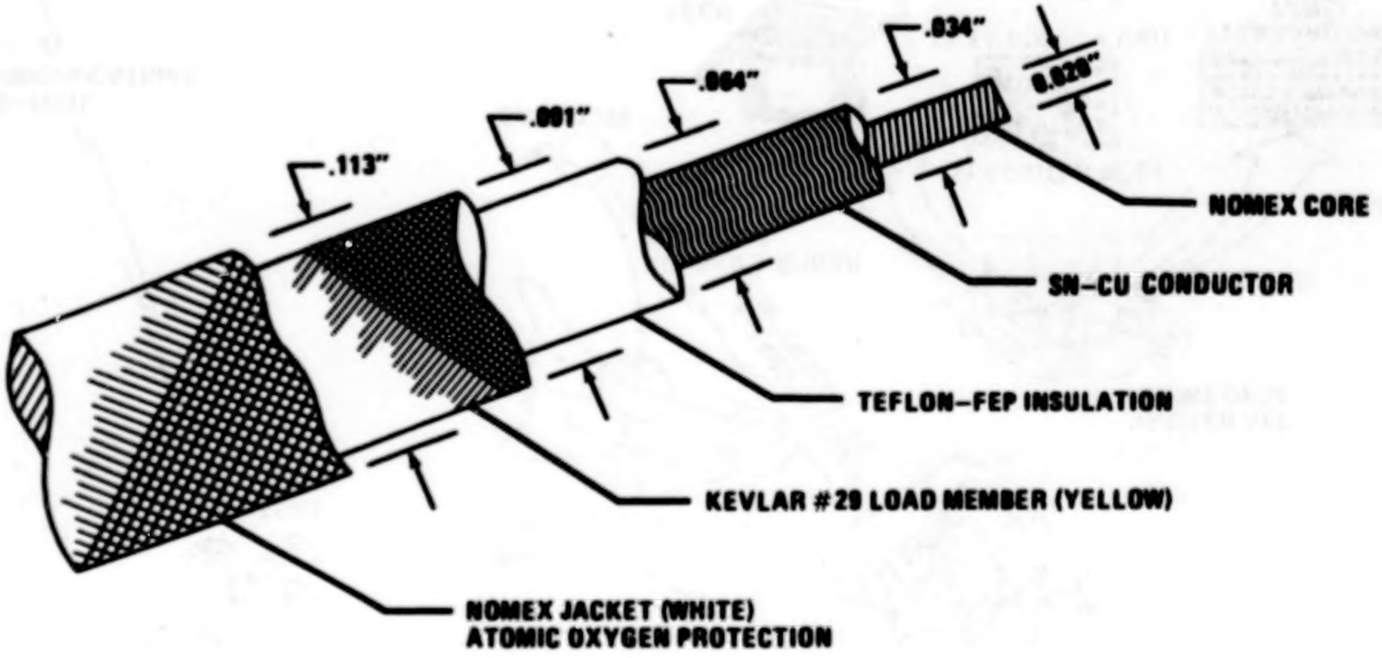
TETHERED SATELLITE SYSTEM MAJOR ELEMENTS/CAPABILITY

NAME: JAMES M. SISSON
DATE: OCTOBER 1985

- DEPLOYER (CONTINUED)
  - BOOM
    - LENGTH – 12 METERS
    - EXTENDABLE/RETRACTABLE
    - ARTICULATED LONGERON DESIGN
    - 60 CM STOP CAPABILITY
    - ENCLOSES SATELLITE UMBILICALS
    - JETTISONABLE
    - REDUNDANT MOTOR DRIVES
  - TETHER
    - GENERAL CORE – MULTI–STRAND NOMEX, 1200 DENIER
    - CONDUCTOR – 10 STRANDS # 34 AWG TIN COATED COPPER, HIGH HELIX ANGLE (5 TURNS/IN)
    - CONDUCTOR INSULATION – EXTRUDED TEFLON FEP
    - LOAD MEMBER – BRAIDED KEVLAR # 29 (YELLOW) 400 LB BREAKSTRENGTH
    - PROTECTIVE OUTER JACKET – BRAIDED NOMEX (WHITE)

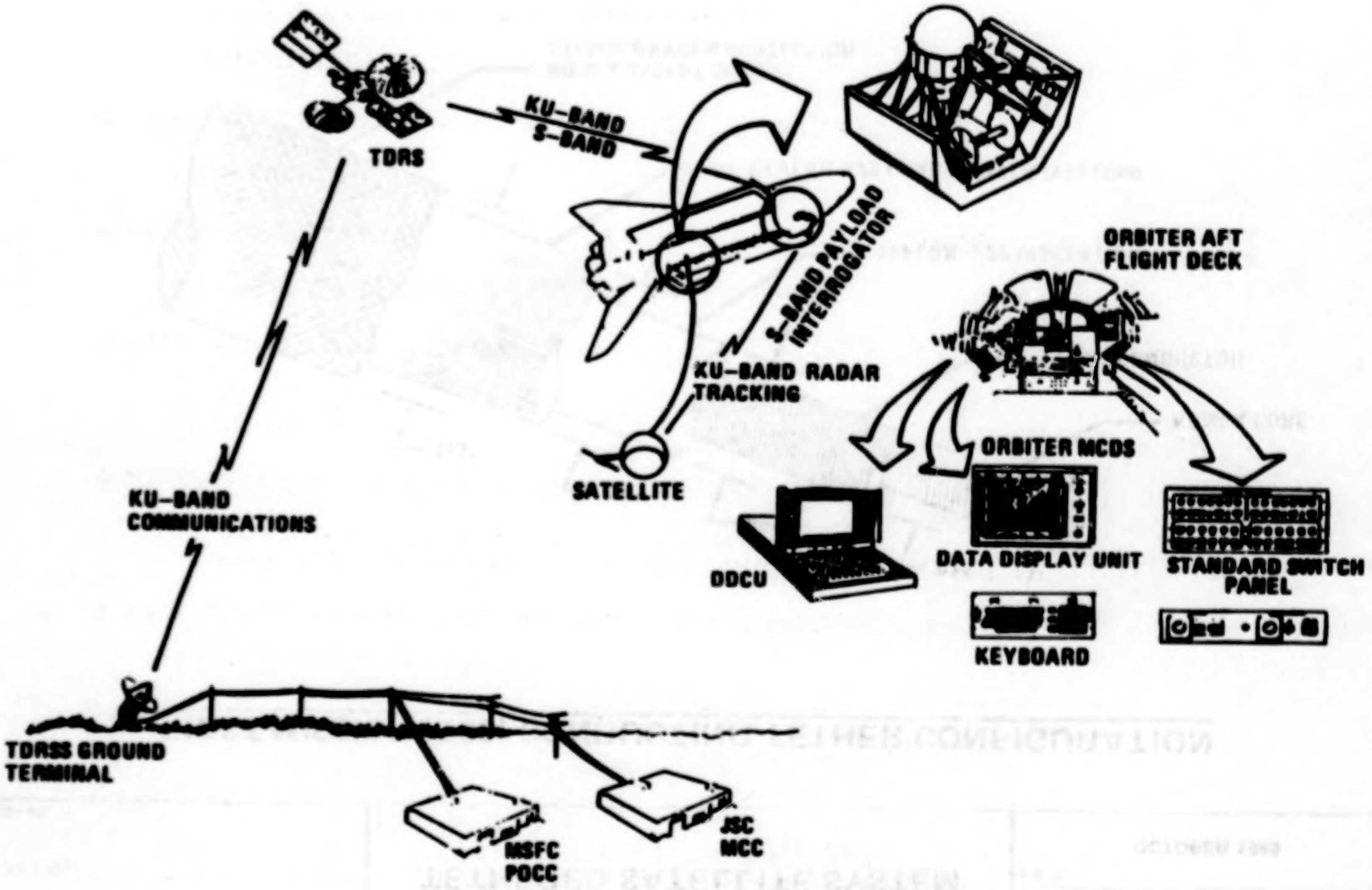
ORGANIZATION: FA31	MARSHALL SPACE FLIGHT CENTER	NAME: J. SISSON
CHART NO.: [illegible]	TETHERED SATELLITE SYSTEM	DATE: OCTOBER 1985

FIRST MISSION (TSS) CONDUCTING TETHER CONFIGURATION


.113"
.091"
.064"
.034"
0.026"
NOMEX CORE
SN–CU CONDUCTOR
TEFLON–FEP INSULATION
KEVLAR #29 LOAD MEMBER (YELLOW)
NOMEX JACKET (WHITE)
ATOMIC OXYGEN PROTECTION

[illegible]

DESIGN OVERVIEW – TSS/ORBITER/GROUND INTERFACES


TDRS
KU–BAND
S–BAND
KU–BAND COMMUNICATIONS
S–BAND PAYLOAD INTERROGATOR
KU–BAND RADAR TRACKING
SATELLITE
ORBITER AFT FLIGHT DECK
ORBITER MCDS
DDCU
DATA DISPLAY UNIT
KEYBOARD
STANDARD SWITCH PANEL
TDRSS GROUND TERMINAL
MSFC POCC
JSC MCC

ORGANIZATION: FA31	MARSHALL SPACE FLIGHT CENTER **TETHERED SATELLITE SYSTEM PROJECT STATUS REVIEW**	NAME: J. SISSON
CHART NO.: 2020–05		DATE: OCTOBER 1985

MISSION OPERATIONS

- WILL USE HUNTSVILLE OPERATIONS SUPPORT CENTER (HOSC)
  - PROVIDE ENGINEERING SUPPORT FOR THE SATELLITE, DEPLOYER, AND THE ENHANCED MDM PALLET (EMP) SYSTEMS
- WILL USE MSFC PAYLOAD OPERATIONS SUPPORT CENTER (POCC)
  - PROVIDE SUPPORT TO SATELLITE SCIENCE, SATELLITE CORE EQUIPMENT, DEPLOYER SCIENCE AND DEPLOYER CORE EQUIPMENT
- WILL USE MSFC PAYLOAD CREW TRAINING COMPLEX (PCTC)
  - PROVIDE TRAINING FOR ON–BOARD CREW
- FLIGHT OPERATIONS WORKING GROUP (FOWG) ESTABLISHED
  - CHAIRED BY S&E
- PAYLOAD OPERATIONS WORKING GROUP (POWG) ESTABLISHED
  - CHAIRED BY JSC
  - SUPPORT DEPLOYMENT AND RETRIEVAL
  - SUPPORT DETACHED SATELLITE OPERATIONS

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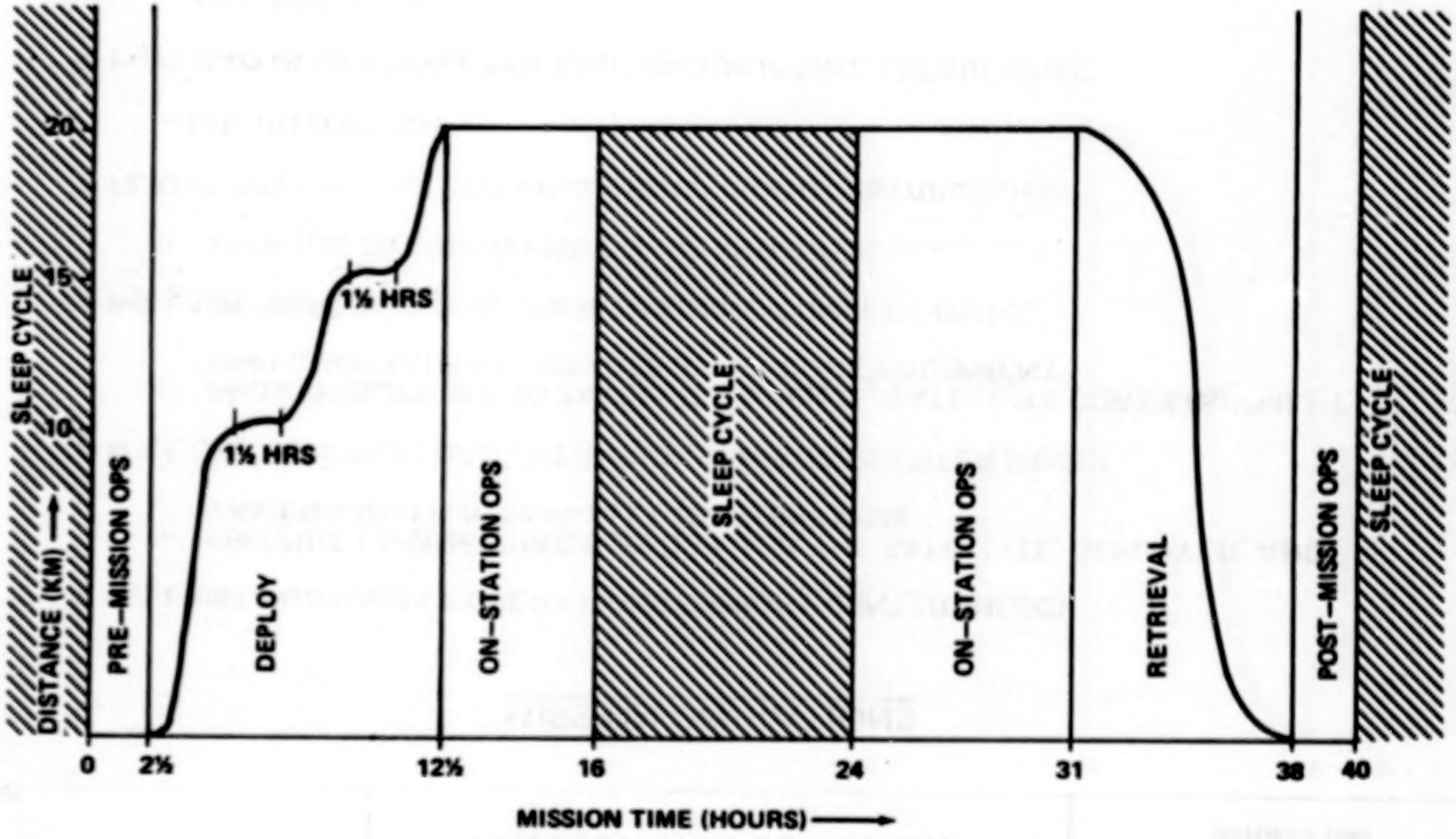
TSS—1 TIMELINE



ORGANIZATION: FA31	MARSHALL SPACE FLIGHT CENTER	NAME J. SISSON
CHART NO.: 2088–85	**TETHERED SATELLITE SYSTEM PRINCIPAL INVESTIGATION SCIENCE**	DATE: OCTOBER 1985

- **SATELLITE INSTRUMENTATION**
  - **ELECTRODYNAMIC TETHER EFFECTS – DOBROWOLNY (CNR)**

– 3 AXIS DIPOLES	– A. C. ELECTRIC FIELDS & ELECTROSTATIC WAVES
– 2 AXIS SEARCH COILS	– A. C. MAGNETIC FIELDS
– (2) LANGMUIR PROBES	– e^- DENSITY, e^- ENERGY, POTENTIAL DISTRIBUTION

  - **PLASMA ELECTRODYNAMICS – STONE (MSFC)**

– DIFFERENTIAL ION FLUX PROBE	– ION ENERGY TEMPERATURE AND DENSITY VS INCIDENCE ANGLE
– (8) SOFT PARTICLE ENERGY SPECTOMETER	– CHARGED PARTICLE ENERGY DISTRIBUTION AND SPACE POTENTIAL

  - **MAGNETIC FIELDS – MARIANI (U. ROME)**

– TRIAXIAL FLUXGATE MAGNETOMETER	– VECTOR MAGNETIC FIELDS

- **ORBITER INSTRUMENTATION**
  - **VEHICLE CHARGING AND POTENTIAL – BANKS (STANFORD)**

– (2) SPOT CHARGE AND CURRENT PROBES	– LOCAL CURRENT AND POTENTIAL
– SPHERICAL LANGMUIR PROBE	– VEHICLE POTENTIAL, ION DENSITY AND TEMPERATURE
– FAST PULSE ELECTRON GUN	

- **ELECTRODYNAMIC THEORY**
  - **PLASMA COUPLING STUDIES – PAPADOPOULIS (SAI)**

- **TETHER DYNAMICS**
  - **DYNAMIC NOISE STUDIES – GULLAHORN (SAO)**
  - **DYNAMIC NOISE STUDIES – BERGAMASCHI (PADOVA – ITALY)**

- **GROUND BASED OBSERVATIONS**
  - **EM EMISSIONS – ESTES (SAO)**

– ELF RECEIVERS	– DETECT TETHER GENERATED EMISSIONS AT ELF
– MAGNETOMETERS	– DETECT TETHER GENERATED EMISSIONS AT ULF

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TETHERED SATELLITE DESIGN

Gianfranco Manarini
PSN

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SATELLITE CONCEPT

A) MISSION OBJECTIVES

- ENGINEERING TEST

  TO TEST THE CAPABILITY OF THE SATELLITE TO PERFORM A VARIETY OF SPACE OPERATIONS TO BE ACCOMPLISHED FROM THE SHUTTLE, CONSIDERING:

  - USE OF THE SATELLITE WITH MAN-IN-LOOP AND CLOSED LOOP MODES -
  - DEPLOYMENT (TOWARD OR AWAY FROM EARTH, UP TO 100 KM), STATION-KEEPING, RETRIEVAL AND CONTROL OF THE SATELLITE.

- SCIENTIFIC PAYLOADS

  TO PERFORM EXPERIMENTS AND SCIENTIFIC INVESTIGATION FOR APPLICATIONS SUCH AS:

  - MAGNETOMETRY
  - ELECTRODYNAMICS
  - ATMOSPHERIC SCIENCE
  - CHEMICAL RELEASE
  - COMMUNICATIONS
  - PLASMAPHYSICS
  - DYNAMIC ENVIRONMENT
  - POWER AND THRUST GENERATION

SATELLITE CONCEPT (CONT'D)

B) REUSABLE

THE TSS-S WILL BE REUSED FOR AT LEAST 3 MISSIONS AFTER RECONFIGURATION AND REFURBISHMENT BY CHANGING THE PECULIAR MISSION ITEMS: THERMAL CONTROL, FIXED BOOM FOR EXPERIMENTS, AERODYNAMIC TAIL FOR YAW ATTITUDE CONTROL, EXTERNAL SKIN, EXPERIMENTS, ANY OTHER FEATURE

C) MODULES

THE TSS-S IS COMPOSED OF THREE MODULES IN ORDER TO ALLOW INDEPENDENT INTEGRATION OF A SINGLE MODULE AND TO FACILITATE THE REFURBISHMENT AND RECONFIGURATION BETWEEN THE FLIGHTS.
THE THREE MODULES ARE:

- SERVICE MODULE (SM)
- AUXILIARY PROPULSION MODULE (APM)
- PAYLOAD MODULE (PM)

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SATELLITE CAPABILITY

- PAYLOAD

  TOTAL WEIGHT 66 Kg; 2 Kg ON THE FIXED BOOM 1.0 METER LONG (46 Kg FOR ATM MISSION)

  2000 WH OF ENERGY
- THREE AXIS ATTITUDE MEASUREMENT
- ATTITUDE AND SPIN CONTROL AROUND YAW AXIS (NO SPIN CONTROL FOR ATM MISSION)
- SPIN VELOCITY MEASUREMENT (N/A TO ATM MISSION)
- COMMUNICATION WITH ORBITER P.I. VIA S-BAND LINK FOR COMMAND RECEPTION AND TELEMETRY DATA TRANSMISSION

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SATELLITE CAPABILITY (CONT'D)

- CONTROL OF SATELLITE FUNCTIONS
  - MONITORS ACQUISITION
  - AMCS DATA PROCESSING
  - COMMAND DISTRIBUTION

- ENGINEERING DATA MONITORING: SATELLITE TEMPERATURES, GN_2 PRESSURE, BATTERIES VOLTAGE, ENERGY AND FUEL CONSUMPTION

- OPERATIONAL SUPPORT TO THE TSS
  - IN LINE THRUSTERS TO AVOID TETHER TENSION LOWER THAN 2N
  - SIDE THRUSTERS FOR IN-PLANE AND OUT-OF-PLANE OSCILLATION DAMPING

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SATELLITE EXTERNAL CONFIGURATION

- SPHERICAL, 1.6 METERS DIAMETER
- WEIGHT, 500 Kg INCLUDING EXPERIMENTS
- 8 COVERING PETALS TO ALLOW THE SUBSYSTEMS AND PAYLOAD INTEGRATION/REFURBISHMENT
- 4 ACCESS DOORS FOR BATTERIES INTEGRATION AND CHANGE-OUT
- TETHER ATTACHMENT INTEGRATED IN THE IN-LINE THRUSTERS ASSEMBLY
- EQUATORIAL RING WITH 6 SUPPORTS FOR MECHANICAL INTEGRATION WITH THE DEPLOYER
- 2 SKIN CONNECTORS FOR SATELLITE/DEPLOYER ELECTRICAL CONNECTION PRIOR DEPLOYMENT
- WINDOWS FOR SUN SENSORS (4) AND EARTH SENSORS (2)
- A DEDICATED BOOM FOR S-BAND ANTENNA
- A 1.0 METER FIXED BOOM FOR EXPERIMENT
- AERODYNAMIC TAIL (ONLY FOR ATMOSPHERIC MISSION)

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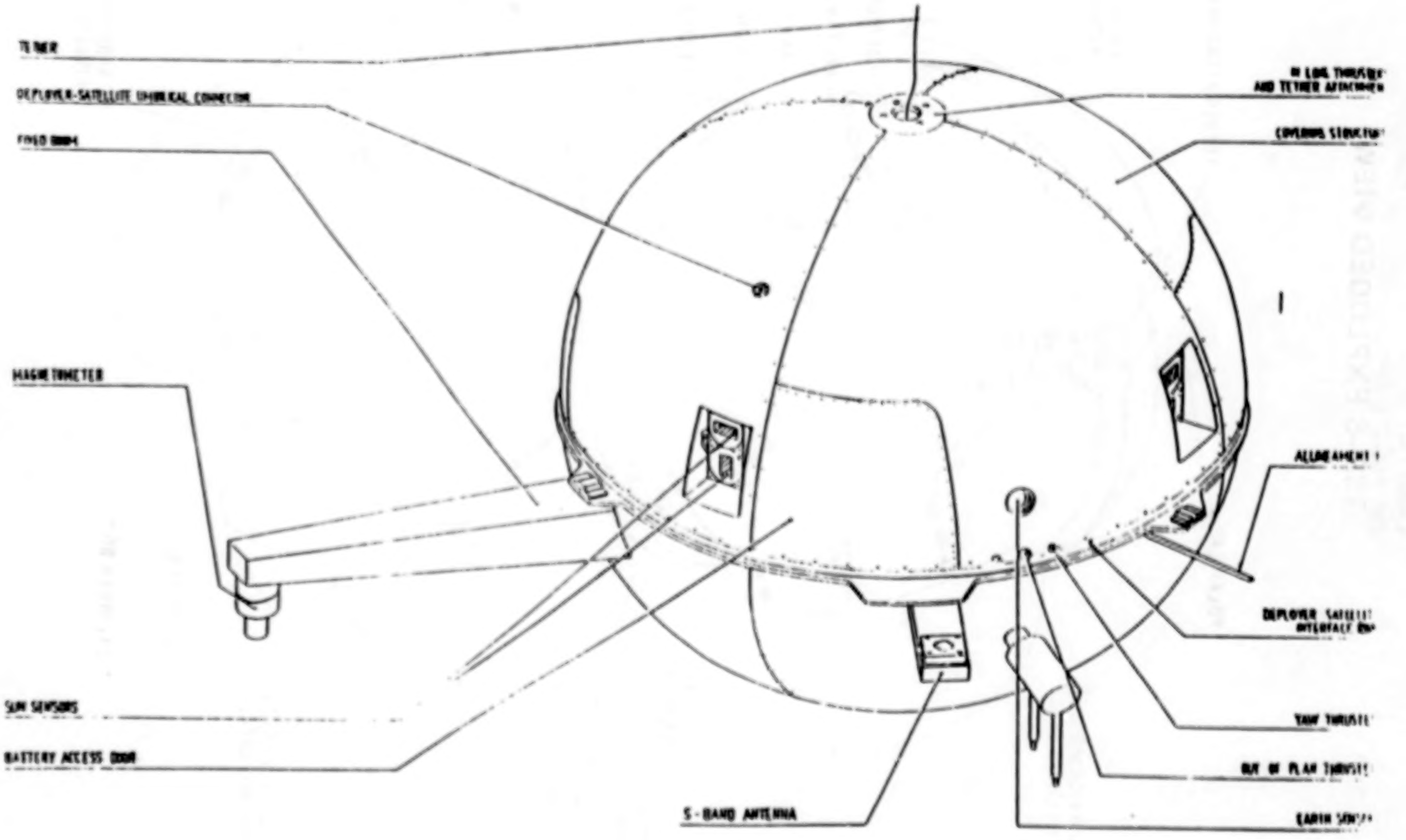
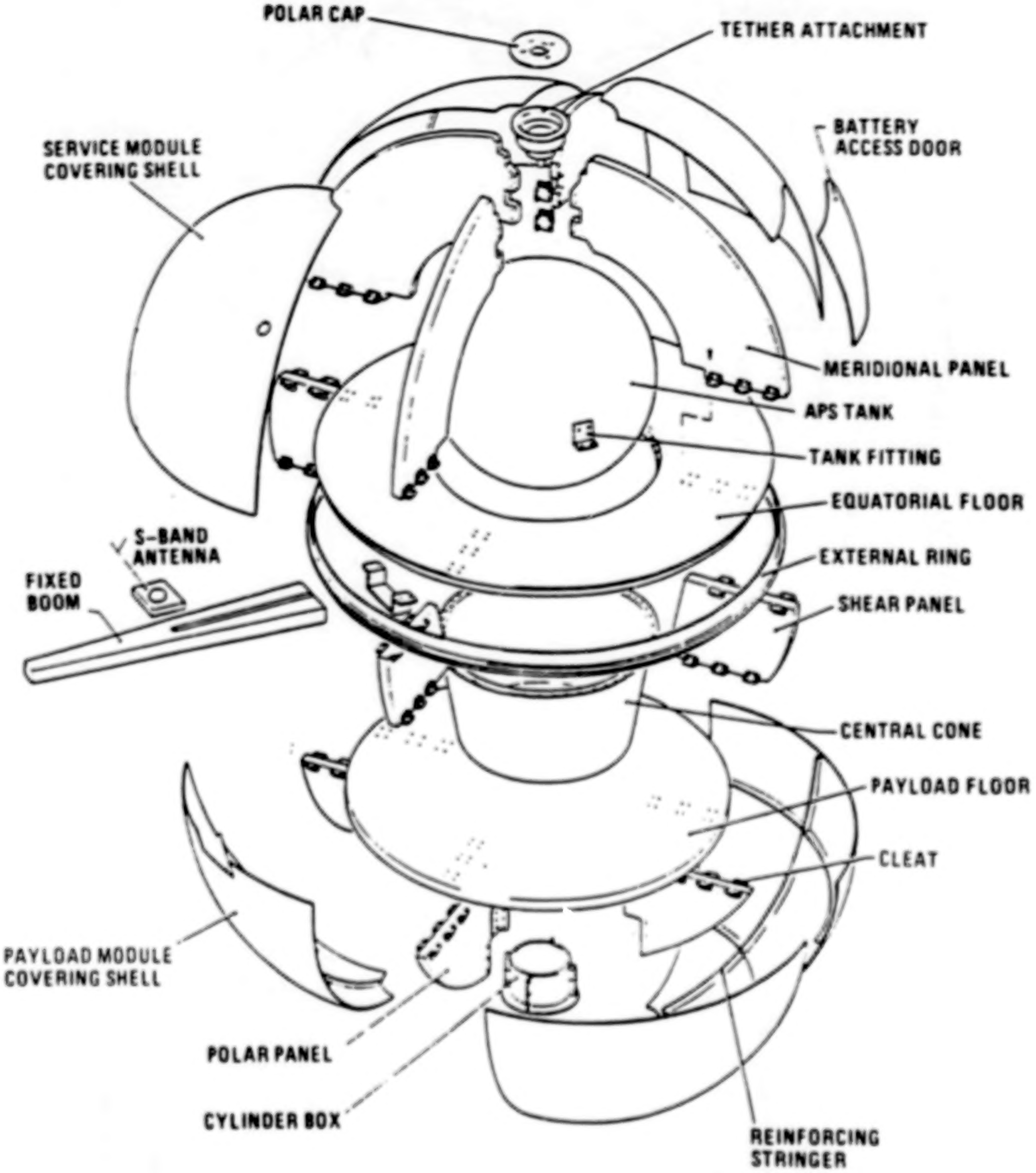
TSS-S ELECTRODYNAMIC CONFIGURATION


TETHER
DEPLOYER-SATELLITE UMBILICAL CONNECTOR
FIXED BOOM
MAGNETOMETER
SUN SENSORS
BATTERY ACCESS DOOR
S-BAND ANTENNA
IN LINE THRUSTER AND TETHER ATTACHMENT
OPENING STRUCTURE
ALIGNMENT
DEPLOYER SATELLITE INTERFACE RING
YAW THRUSTER
OUT OF PLANE THRUSTER
EARTH SENSOR

TSS–S EXPLODED VIEW


POLAR CAP
TETHER ATTACHMENT
BATTERY ACCESS DOOR
SERVICE MODULE COVERING SHELL
MERIDIONAL PANEL
APS TANK
TANK FITTING
EQUATORIAL FLOOR
S-BAND ANTENNA
FIXED BOOM
EXTERNAL RING
SHEAR PANEL
CENTRAL CONE
PAYLOAD FLOOR
CLEAT
PAYLOAD MODULE COVERING SHELL
POLAR PANEL
CYLINDER BOX
REINFORCING STRINGER

ELECTRODYNAMIC SATELLITE INTERNAL LAY-OUT

A) MERIDIONAL PANELS (4) AND EQUATORIAL FLOOR USED FOR SERVICE MODULE LAY-OUT

B) PAYLOAD FLOOR, SHEAR AND POLAR PANELS, FIXED BOOM USED FOR PAYLOAD MODULE LAY-OUT

C) EQUATORIAL FLOOR USED FOR AUXILIARY PROPULSION MODULE

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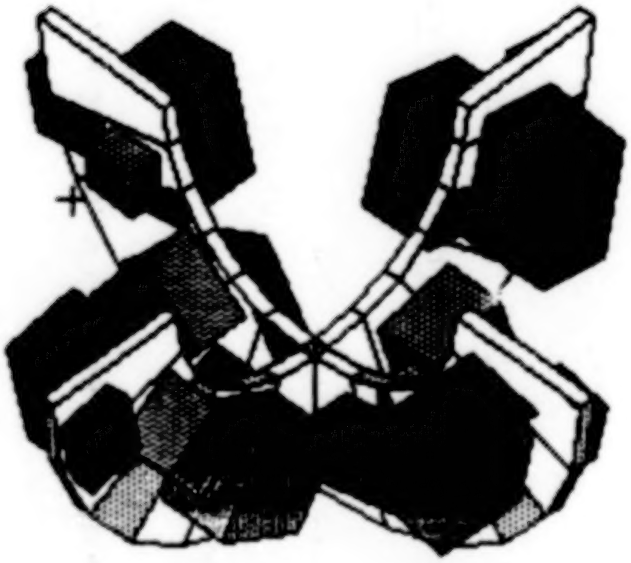

3-10-85	AERITALIA - GSS - SYSTEMS ENGINEERING
	(1) SERVICE MODULE

TSS SATELLITE SCIENCE ACCOMODATION (EDY MISSION)

GEOMETRICAL AND MECHANICAL CAPABILITIES

SCIENCE INSTRUMENTS CAN BE ACCOMODATED ON:

A) EITHER SIDE OF THE FOLLOWING PAYLOAD MODULE ELEMENTS:

- PAYLOAD FLOOR
- FOUR (4) POLAR PANELS
- FOUR (4) SHEAR PANELS, INTERPOSED BETWEEN THE PAYLOAD FLOOR AND THE EQUATORIAL FLOOR.

WITH: - TOTAL FOOTPRINT AREA AVAILABLE: 2.4 M^2
- TOTAL VOLUME AVAILABLE: 0.4 M^3
- TOTAL MASS: 66 Kg

B) THE FIXED 1.0 M LONG BOOM WITH 2 Kg TOTAL MASS CAPABILITY

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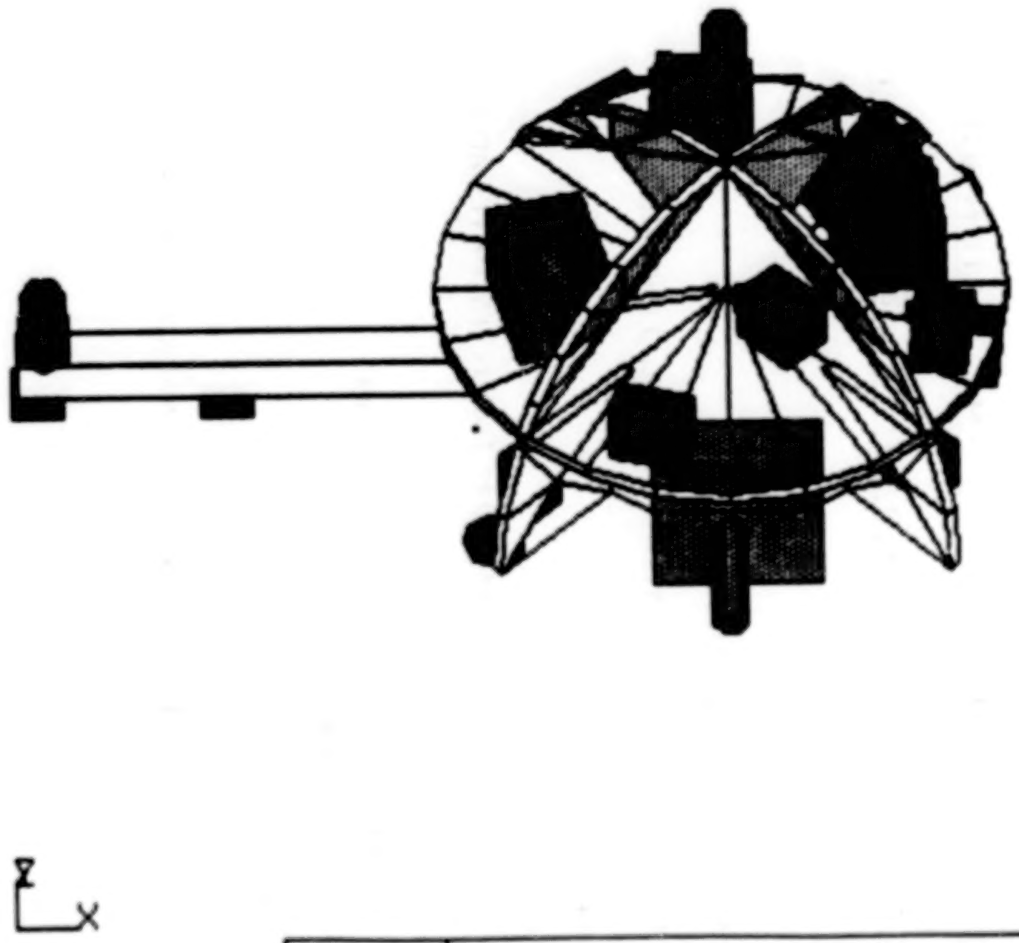

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3-10-85	AERITALIA - GSS - SYSTEMS ENGINEERING
	(3) PL/M AT LAUNCH

SCIENCE FOR THE FIRST TSS ELECTRODYNAMIC MISSION

SCIENTIFIC OBJECTIVES

- STUDY OF ELECTRODYNAMIC INTERACTION BETWEEN THE TSS AND AMBIENT PLASMA
- STUDY OF DYNAMICAL FORCES ACTING ON THE TETHERED SATELLITE

SATELLITE INSTRUMENTATION

- RESEARCH ON ELECTRODYNAMIC TETHER EFFECTS (RETE) - PROF. M. DOBROWOLNY CNR/IFSI - FRASCATI - ROME

  WAVE SENSORS ON TWO EXTENDABLE BOOMS (4 m EACH) TO EXPLORE SPACE CHARGE REGION AROUND SATELLITE.
- TETHER MAGNETIC FIELD MEASUREMENT (TEMAG) - PROF. F. MARIANI - 2ND UNIVERSITY OF ROME - TOR VERGATA - ROME

  TWO MAGNETOMETERS ON FIXED BOOM (85 cm) TO MEASURE MAGNETIC FIELD AND DYNAMICS OF TETHERED SATELLITE.

  RESEARCH ON ORBITAL PLASMA - ELECTRODYNAMICS (ROPE) - DR. N. STONE - NASA/MSFC HUNTSVILLE - ALABAMA

  PARTICLE SENSORS ON FIXED BOOM (85 cm) AND ON SATELLITE TO STUDY SATELLITE PLASMA INTERACTION.

SCIENCE FOR THE FIRST TSS ELECTRODYNAMIC MISSION (CONT'D)

DEPLOYER INSTRUMENTATION

- SHUTTLE ELECTRODYNAMIC TETHER SYSTEM (SETS) - PROF. P. BANKS - STANFORD UNIVERSITY - STANFORD - CALIFORNIA

  VARIOUS INSTRUMENTS TO STUDY TETHER CURRENT - VOLTAGE CHARACTERISTICS, CHARGE CONTROL AND EMISSION AT ORBITER, OTHER PLASMA AND IONOSPHERIC PROCESSES.

THEORY AND GROUND - BASED OBSERVATIONS

- THEORY AND MODELING IN SUPPORT OF TETHER - PROF. K. PAPADOPOULOS - SCIENCE APPLICATIONS, INC. - McLEAN - VIRGINIA
- INVESTIGATION ON TSS DYNAMICS - PROF. S. BERGAMASCHI - UNIVERSITY OF PADOVA PADOVA
- INVESTIGATION AND MEASUREMENT OF DYNAMIC NOISE IN TSS - DR. G. GULLAHORN - SAO CAMBRIDGE - MASSACHUSSETS
- DETECTION OF ELECTRODYNAMIC ULF/ELF EMISSIONS BY THE TETHER - PROF. G. TACCONI UNIVERSITY OF GENOVA - GENOVA
- INVESTIGATION OF ELECTRODYNAMIC EMISSIONS BY THE TETHER - DR. R. ESTES - SAO CAMBRIDGE MASSACHUSSETS.

ITALY IS RESPONSIBLE FOR THE INTEGRATION OF THE SCIENTIFIC INSTRUMENTATION ON THE SATELLITE

TSS CORE EQUIPMENT

TETHER CURRENT-VOLTAGE CONTROL (TCVC) SYSTEM

PURPOSE

FOR THE ELECTRODYNAMIC MISSIONS THE TCVC SYSTEM WILL SPECIFICALLY ALLOW INVESTIGATION OF THE TSS-S ELECTRICAL POTENTIAL BY CONTROLLING THE CURRENT THAT FLOWS BETWEEN THE SATELLITE AND THE ORBITER THROUGH THE TETHER AS A RESULT OF THE EMF GENERATED (UP TO 5 KV) BY MOTION OF THE TSS THROUGH THE GEOMAGNETIC FIELD

THIS FUNCTION IS FUNDAMENTAL TO THE OPERATION OF THE ELECTRODYNAMIC TETHER AND IS ESSENTIAL FOR THE TSS SCIENTIFIC INVESTIGATIONS.

THREE-AXIS ACCELEROMETER-GYRO SYSTEM

PURPOSE

THE THREE-AXIS ACCELEROMETER-GYRO SYSTEM WILL PROVIDE A HIGHLY ACCURATE ASSESSMENT OF DYNAMIC PERTURBATION TO THE MOTION OF THE TETHERED SATELLITE.

THIS INFORMATION IS REQUIRED TO DETERMINE THE SUITABILITY OF THE TETHERED SATELLITE AS A PLATFORM FOR A VARIETY OF INVESTIGATIONS OF CRUSTAL - INDUCED MAGNETIC AND GRAVITATIONAL EFFECTS.

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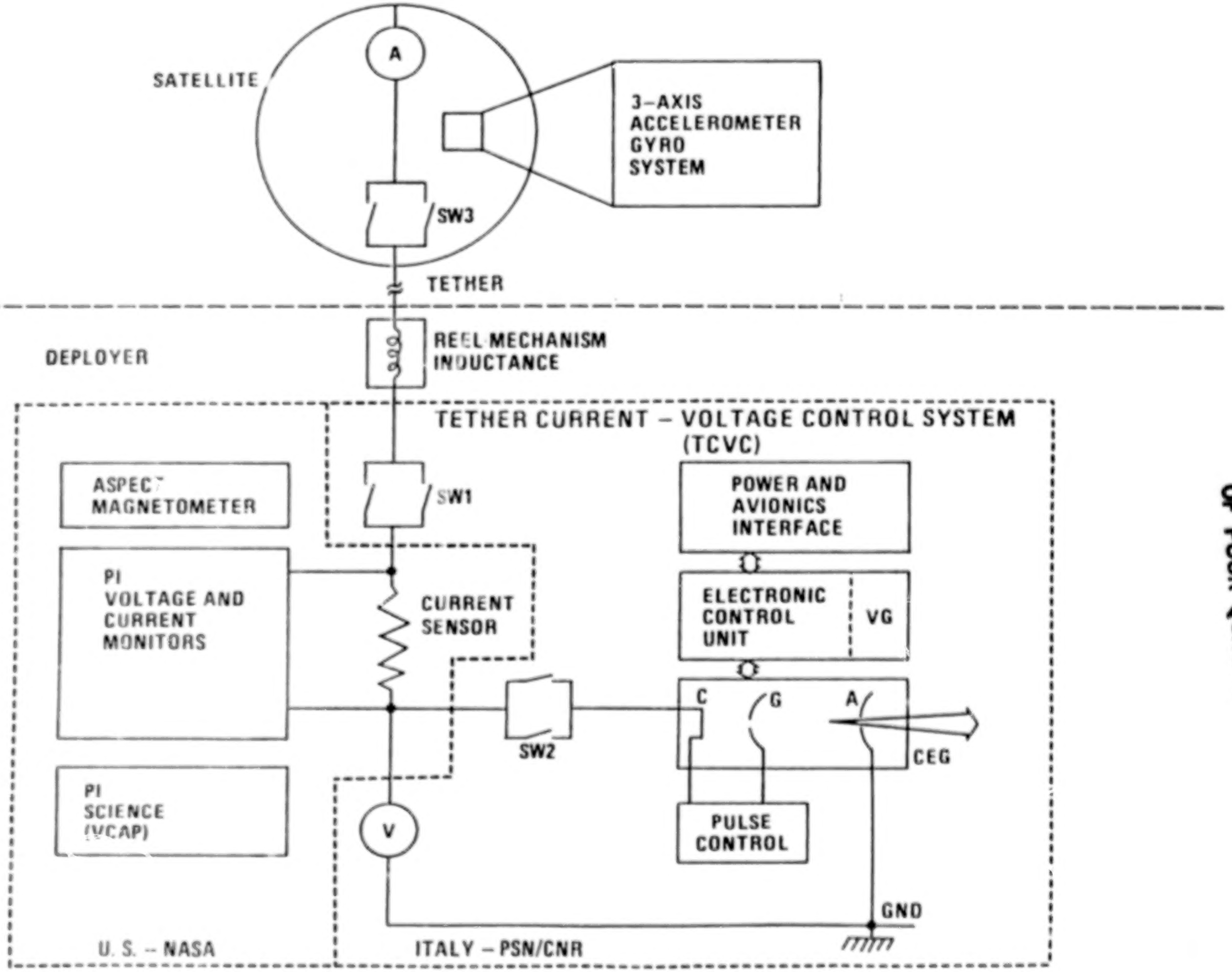
TSS CORE EQUIPMENT
(FIRST MISSION)


SATELLITE
A
3–AXIS ACCELEROMETER GYRO SYSTEM
SW3
TETHER
DEPLOYER
REEL MECHANISM INDUCTANCE
TETHER CURRENT – VOLTAGE CONTROL SYSTEM (TCVC)
ASPECT MAGNETOMETER
SW1
PI VOLTAGE AND CURRENT MONITORS
CURRENT SENSOR
POWER AND AVIONICS INTERFACE
ELECTRONIC CONTROL UNIT
VG
SW2
C
G
A
CEG
PI SCIENCE (VCAP)
V
PULSE CONTROL
GND
U. S. – NASA
ITALY – PSN/CNR

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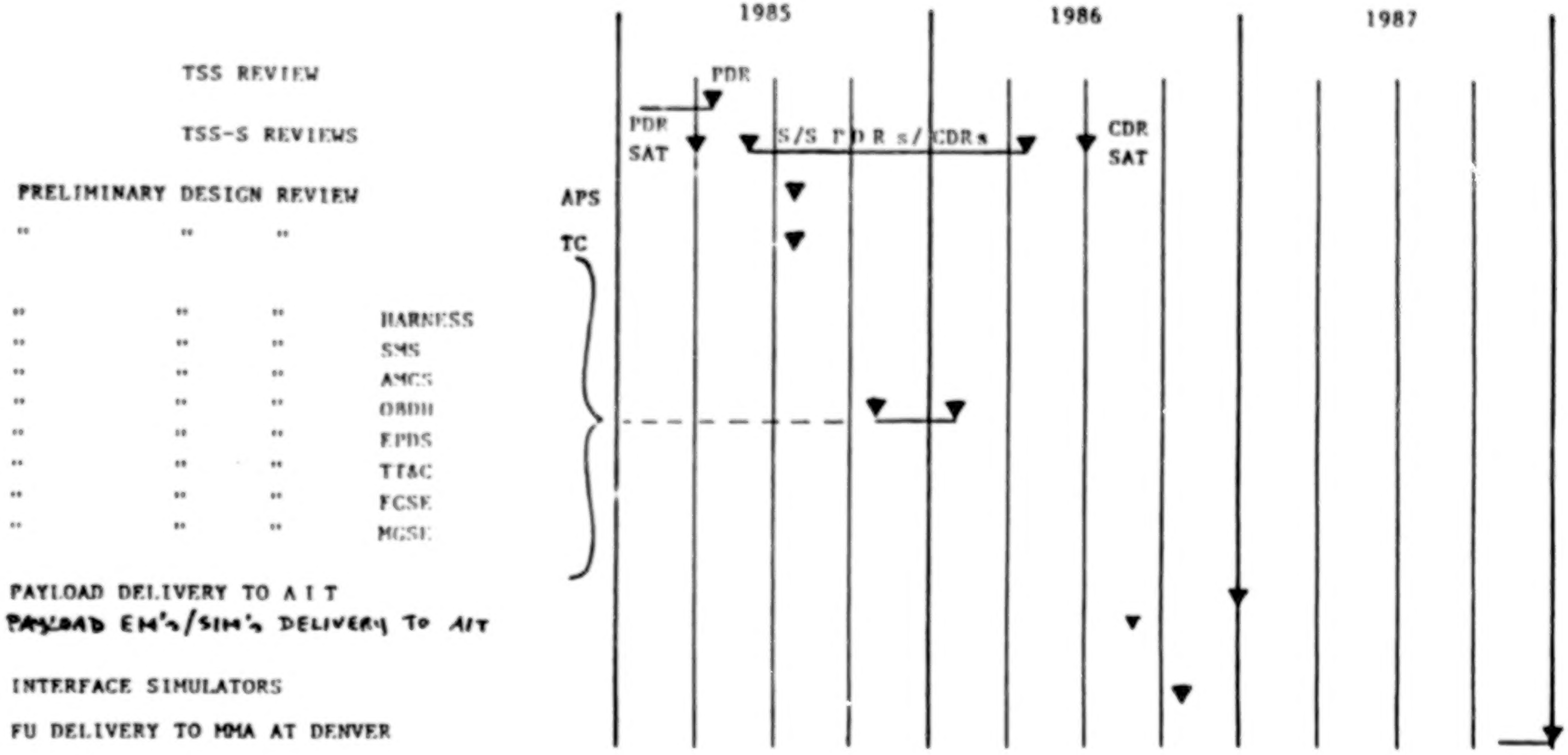
SATELLITE SCHEDULE (MILESTONE)



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TETHER FUNDAMENTALS

Joe Carroll
Energy Science Labs

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PLENARY SESSION -- TETHER FUNDAMENTALS PRESENTATION

Joseph A. Carroll
Energy Science Laboratories, Inc.
11404 Sorrento Valley Rd., #112
San Diego, CA 92121

Buongiorno.

When I was finishing college 15 years ago, I had an interest in some space-tether concepts which I guess I had first heard of through science fiction. But I decided not to pursue them at that time because I thought that there was simply no way that anybody would ever take them seriously, even though they seemed to be physically possible. And then I found out several years ago that tethers were beginning to be taken seriously.

We are indebted to Professor Colombo for many things, but I think the greatest of them is that he spent the last nine years of his life convincing people that tethers are indeed something worth taking seriously. Many of his analyses on tether dynamics may have been difficult to do, but his greatest accomplishment really seems to be simply this: that he got the aerospace community to look seriously at tethers as something not just for science fiction authors but also for engineers and even for national space programs. It is amazing.

I have just one very basic overall point to make on the subject of tether fundamentals. A simple slogan or way of putting it is that tethers may be one-dimensional physically, but analytically they are very, very multi-dimensional. For example, I have a new tether material here--Spectra 900 fiber--which has a higher strength-to-weight ratio than Kevlar. But it has two idiosyncrasies that limit its applications: it rapidly loses strength above room temperature, and it is very sensitive to atomic oxygen. These limitations may seem extraneous, but they are real--and may be crucial in some applications.

So the point of this presentation is going to be that in order to make these tether applications work, we have to "lose our technological innocence" or "engineering innocence"--and not just in one particular area, but in at least a dozen different areas. All the things that I'm going to say in the rest of the talk are just examples, one after another, of the many different ways in which we have to lose our innocence technologically, in order to find out which tether applications are truly practical.

We are here in the city of Venice which has an illustrious history that is highly tied to its accomplishments in maritime technology and sailing. Tethers, ropes, cables, hausers--and ways of using them well--are intimately tied to the history of Venice. We at this workshop are basically where Venice was over a thousand years ago: 90% or maybe even 99% of the things that we are going to consider or try to do are not going to work. But that doesn't matter because there are so many possibilities that, even if only 1% of them work out, we can end up with a technology which is as rich as sailing technology, and which perhaps will have as many effective applications for ropes, strings, tethers, cables, and so forth, as sailing technology found for them over a 1,000 year period in Venice.

Now as my first example, look at gravity-gradient effects. We find that they are there whether we want them or not. We may want a micro-gee facility in low earth orbit. We find that, for example, if we want less than one ten-millionth of a gee, the maximum vertical dimension over which we can have that is quite small: about .5 meters, or .25 meter above and below the CG of a space station. If you relax the requirements to 1E-5 gee, you still can't meet that requirement over a vertical distance greater than about 50 meters, or something less than half the height of the planned space station. This is an idiosyncracy of being in a low orbit. It may turn out to be crucial in some applications, and may be entirely irrelevant in others.

As shown in the figure, gravity-gradient forces are simply the difference between centrifugal force, which increases linearly as you go out along the structure, and the gravity force, which increases as you go inward. These two forces cancel out precisely only at one place, which is very nearly the CG of the structure. Above or below that point you have a force which very nearly scales with the vertical distance from the CG. So at the bottom of the long cylinder shown in the figure, you can stand up, with your feet oriented down; at the middle, you can float; and at the top, "down" happens to be outward. This can be put much more simply to highlight the counter-intuitive aspects of tethers: you can only climb halfway up a tether; beyond that you are "really" going down--and you can prove it by sliding the rest of the way!

When I say "counter-intuitive," I really mean "counter to the untrained intuition." One of the really remarkable things about human beings is the extent to which they can--and do--train their intuitions. A good experienced pilot knows what to do in ordinary cases and in emergencies because his intuition is trained. He has a feeling or image of what is going to happen when he does a certain thing to the plane. And part of what we are going to be doing in the next three days, and in the next ten years, is training our intuitions in this new area, just as a pilot trains his by practice in a new plane.

Note: Most of the following viewgraphs are from the
Guidebook for Analysis of Tether Applications
(prepared by the speaker for Martin Marietta)

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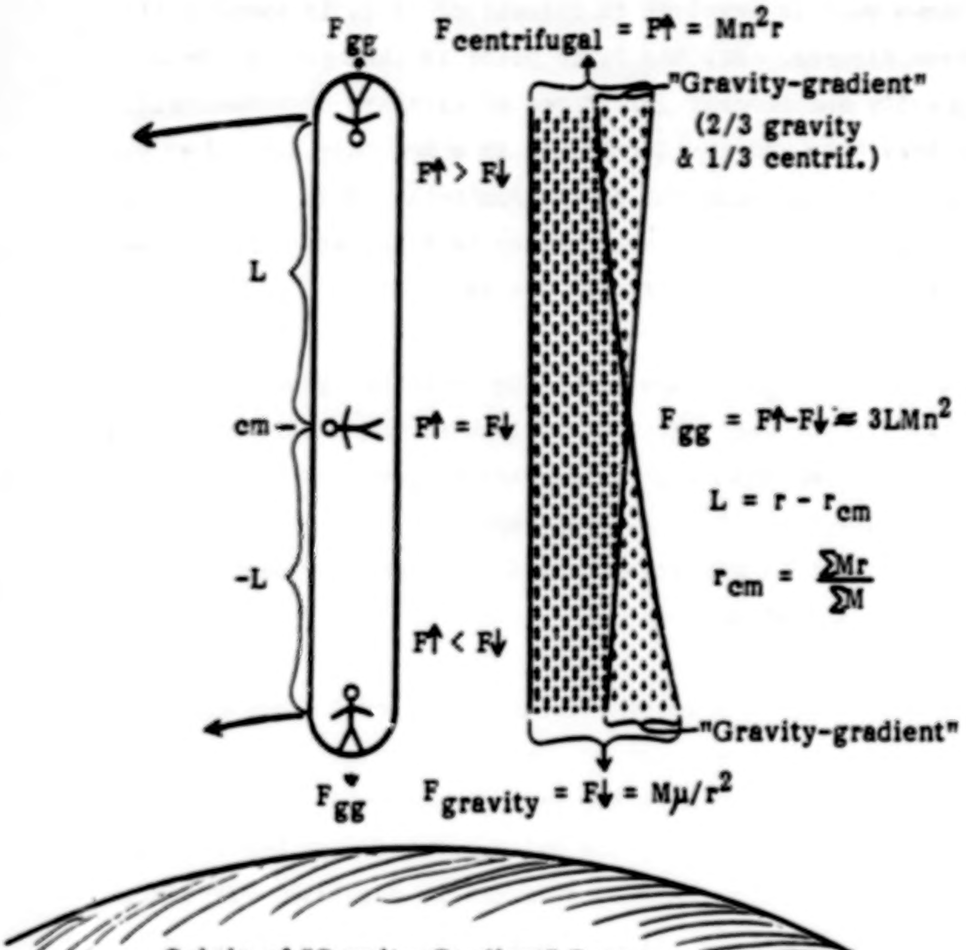
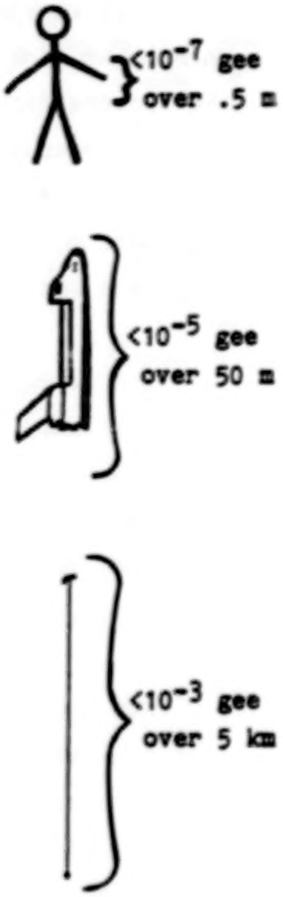
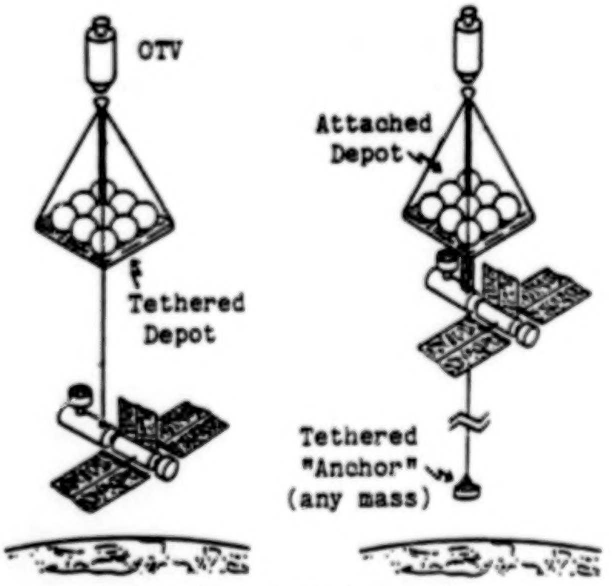
Gravity Gradient Effects


F_{gg}
$F_{centrifugal} = F\uparrow = Mn^2r$
"Gravity-gradient"
(2/3 gravity & 1/3 centrif.)
$F\uparrow > F\downarrow$
L
cm
$F\uparrow = F\downarrow$
$F_{gg} = F\uparrow - F\downarrow \approx 3LMn^2$
$L = r - r_{cm}$
$r_{cm} = \frac{\Sigma Mr}{\Sigma M}$
-L
$F\uparrow < F\downarrow$
"Gravity-gradient"
F_{gg}
$F_{gravity} = F\downarrow = M\mu/r^2$

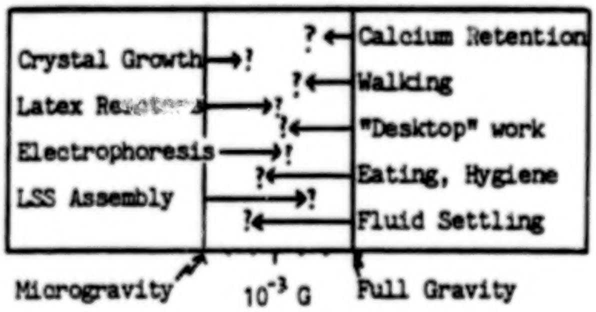
Origin of "Gravity-Gradient" Forces


$<10^{-7}$ gee over .5 m
$<10^{-5}$ gee over 50 m
$<10^{-3}$ gee over 5 km

Magnitude of Gravity Gradient Effects in LEO


OTV
Tethered Depot
Attached Depot
Tethered "Anchor" (any mass)

Two Propellant-Settling Options


Crystal Growth
Latex Reactors
Electrophoresis
LSS Assembly
Calcium Retention
Walking
"Desktop" work
Eating, Hygiene
Fluid Settling
Microgravity
10^{-3} G
Full Gravity

Potential Overlap of Regions for Low-Gee & Gee-Dependent Operations

This viewgraph shows what is involved in libration. I could spend half an hour on each of these figures. But the basic point is that you can draw the vectors for the gravity and centrifugal forces at each end of a dumbbell. When you compute what they are, and the directions in which they act, then you find that there is a net force at each end of the dumbbell. This force has a component aligned with the tether that causes tether tension, and a restoring component which tends to swing you back towards the vertical.

The forces are very small, and so the resulting pendulum dynamics are, well, not very exciting. If you want excitement, look at the minute hand of a clock, because it rotates faster than a gravity-gradient pendulum does. It's good to keep in mind this image--that in a local-vertical, local-horizontal reference frame, the rotation of a gravity-gradient pendulum is slower than the rotation of the minute hand of a clock.

One subtle effect that turns out to be important for several reasons is that the tension in an elongated object varies during libration. As shown at bottom left, the tension can go up by a factor of three (compared to a hanging dumbbell) during the middle of a wide prograde swing. But during the return (retrograde) swing, the tension on a dumbbell beam can go negative. If the dumbbell beam is a tether, the tether will go slack. This ends up being a problem with some applications. In others, it may never be a problem--either the libration isn't wide enough, or you retrieve the tether to take in slack, or you convert the swing into a spin before you ever start to go retrograde. So there are constraints, and there are sometimes work-arounds, and sometimes these work-arounds suggest new ideas, and you go on from there.

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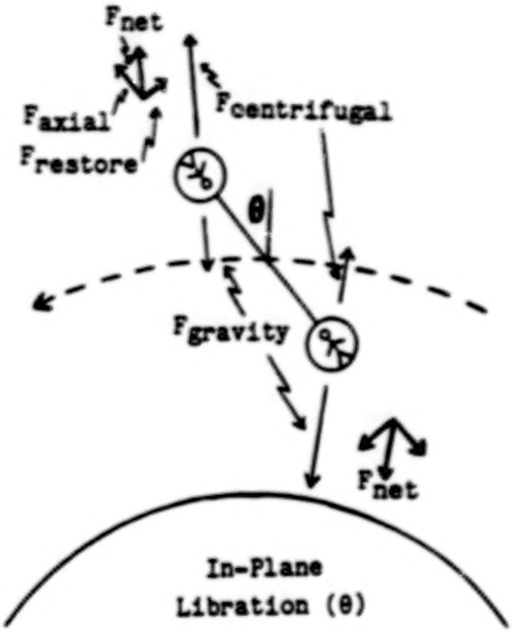
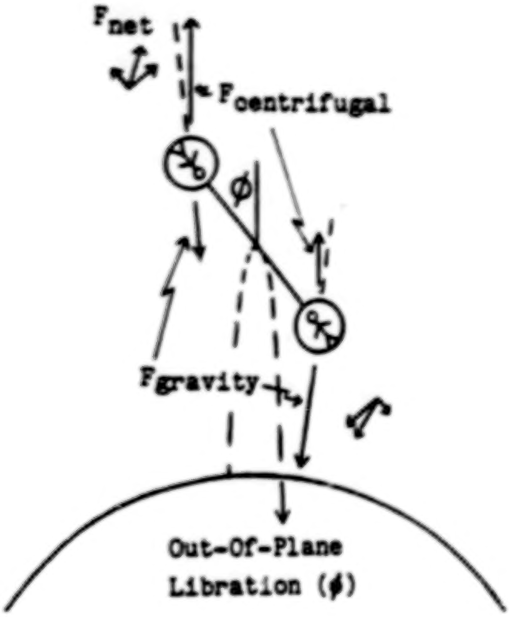
Dumbbell Libration in Circular Orbit


Fnet
Faxial
Frestore
Fcentrifugal
θ
Fgravity
Fnet
In-Plane
Libration (θ)


Fnet
Fcentrifugal
ϕ
Fgravity
Out-Of-Plane
Libration (ϕ)

$\ddot{\theta} \approx -3n^2\sin\theta\cos\theta = -1.5n^2\sin(2\theta)$

$\dot{\theta} \approx \pm\sqrt{3}\, n\sqrt{\sin^2\theta max-\sin^2\theta}$

($\dot{\theta} \approx \pm\sqrt{3}\, n \sin\theta max$ when $\theta=0$)

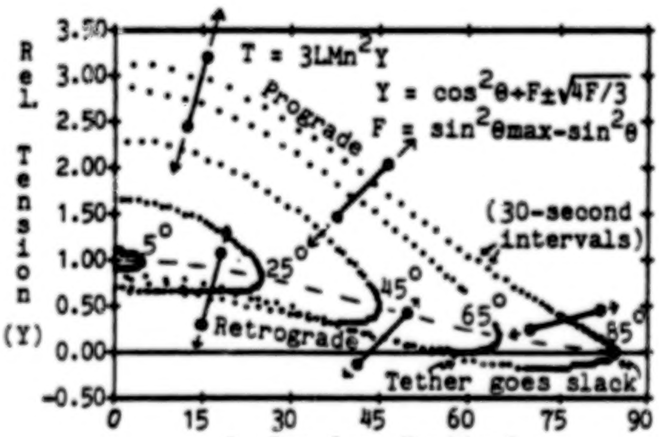
$n_\theta \approx n\sqrt{3\cos\theta max}$

$\ddot{\phi} \approx -4n^2\sin\phi\cos\phi = -2n^2\sin(2\phi)$

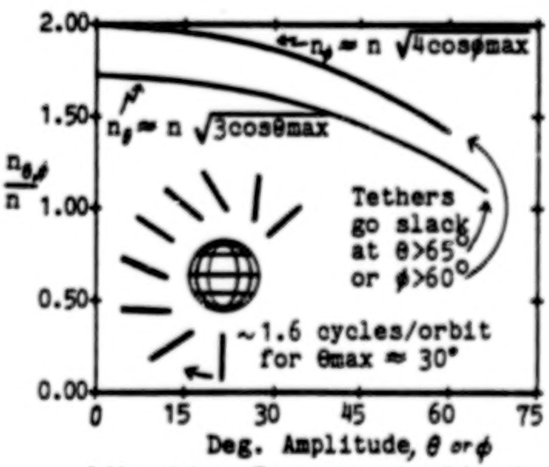
$\dot{\phi} \approx \pm 2n\sqrt{\sin^2\phi max-\sin^2\phi}$

($\dot{\phi} \approx \pm 2n \sin\phi max$ when $\phi=0$)

$n_\phi \approx 2n\sqrt{\cos\phi max}$



Tension Variations in Librating Dumbbells
(compared to tension in hanging dumbbells)



Libration Freq. vs Amplitude

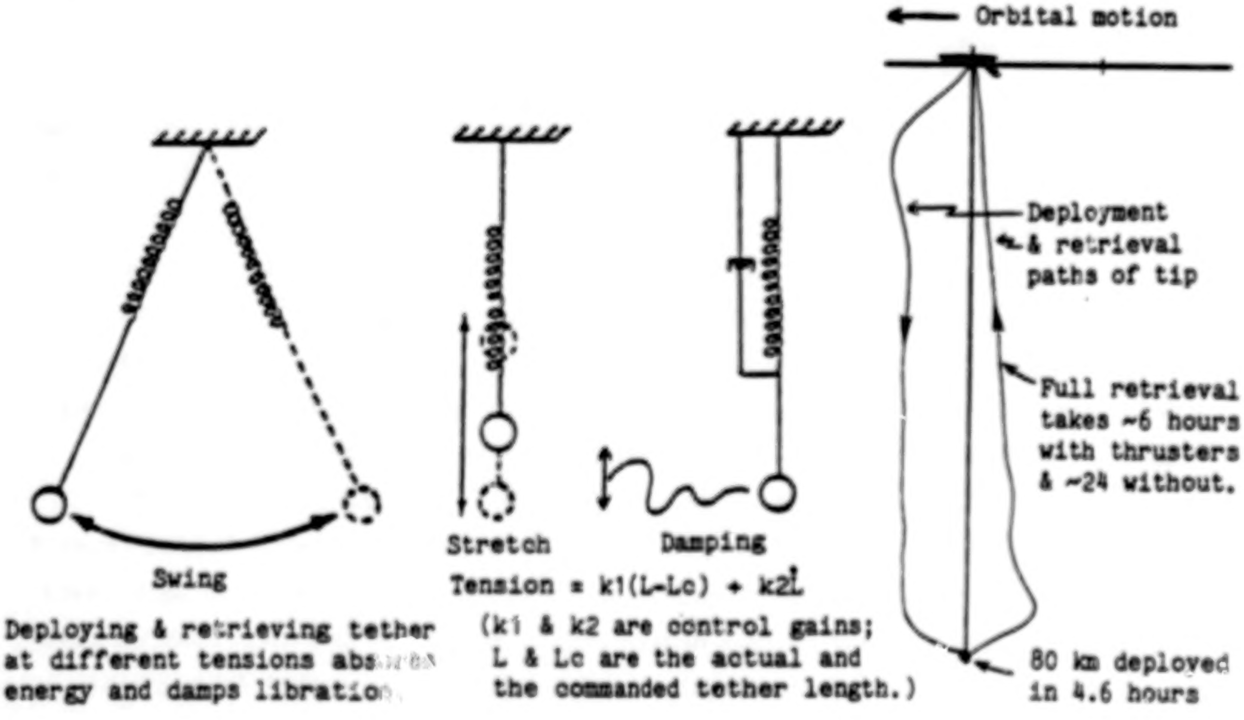
Now we can start thinking about how to control these tether dynamics. The early work on the TSS emphasized tension control, and since then there has also been work on thruster-aided controls. But there also at least four other tools available to use in controlling the behavior of tethers. And even this viewgraph leaves one out: you can retrieve tether fast enough near the end to cause the whole TSS-orbiter system to go into a slow spin. This replaces the gravity-gradient environment (which involves very weak forces when the tether is short) with an artificial-gee environment. The control laws are different, and they may be easier to deal with in some cases. But that gets into shuttle operational issues, and questions like: Is it permissable to make the shuttle spin at a rate of five or six times per hour? This is an example of controls and operational issues that we have to lose our innocence on before we ever find out whether we have a good idea.

Now, as several examples of the importance of operational issues, I have some cartoons which really require no explanation...

Tether Control Strategies

EFFECTIVENESS OF VARIOUS CONTROL CONCEPTS

APPLICATION / CONTROL OUTPUT	Libration		Tether Oscillations		Endmass Attitude Osc.	
	In-plane	Out-of-plane	Longitudinal	Transverse	Pitch & Roll	Yaw
Tension	Strong	Weak	Strong	Strong	Strong	None
	(Note: tension control is weak when tether is short)					
El. Thrust	Only if $M1 \neq M2$		None	Only odd harmonics	None	None
Thruster	Strong, but costly if prolonged			None	Strong, but costly if prolonged	
Movable mass	Good w/short tether		Possible but awkward		None	None
Stiff tether, Movable boom	Strong if tether is very short; weak otherwise					
Aerodynamic	High drag—use only if low altitude needed for other reasons.					


Orbital motion
Deployment & retrieval paths of tip
Full retrieval takes ~6 hours with thrusters & ~24 without.
80 km deployed in 4.6 hours
Swing
Stretch
Damping

Deploying & retrieving tether at different tensions absorbs energy and damps libration.

Tension = $k1(L-Lc) + k2\dot{L}$

(k1 & k2 are control gains; L & Lc are the actual and the commanded tether length.)

TENSION CONTROL FOR LIBRATION DAMPING... AND DEPLOYMENT/RETRIEVAL

These are real issues.

The point is for us to show with high assurance that these cartoons do not represent plausible tether operational failure modes--before someone else suggests that they might. If we do our homework ahead of time, these remain only cartoons. OK?

And here we have a cartoon which highlights another tether operational issue. If we happened to live in a solar system where micrometeoroids were rare, we wouldn't have to worry about this sort of thing. But in many tether applications, it turns out that the longevity of the tether & the feasibility of the given operation entirely depend on micrometeoroid sensitivity. There are some early tether applications I am studying in which the tether mass required to keep this risk below .1% is about 20 times the tether mass needed simply to support the payload.

There is a very ambitious concept proposed by Jerome Pearson, which seems feasible from a dynamics and strength-of-materials point of view . It involves a beanstalk which rises from the moon's surface and supports itself by hanging past the L-1 point into the earth's gravity field. It requires a tapered tether of something at least as strong as Kevlar, but it can be done with current materials. The main problem is that you can invest 3,000 tonnes of tether in making this system and then start deploying it, and it will probably be broken before it is half-way deployed, because it's an immensely long tether with a lot of area and a lot of exposure. Now one can cure this problem by making the tether in the form of a net or a "tensile Eiffel tower," and having automated "linemen" repairing it all the time. But the point here is that the practicality or the design can be driven by the fact that we live in a solar system where, one might say, "the gods throw rocks" (and gravel, and sand, and dust).

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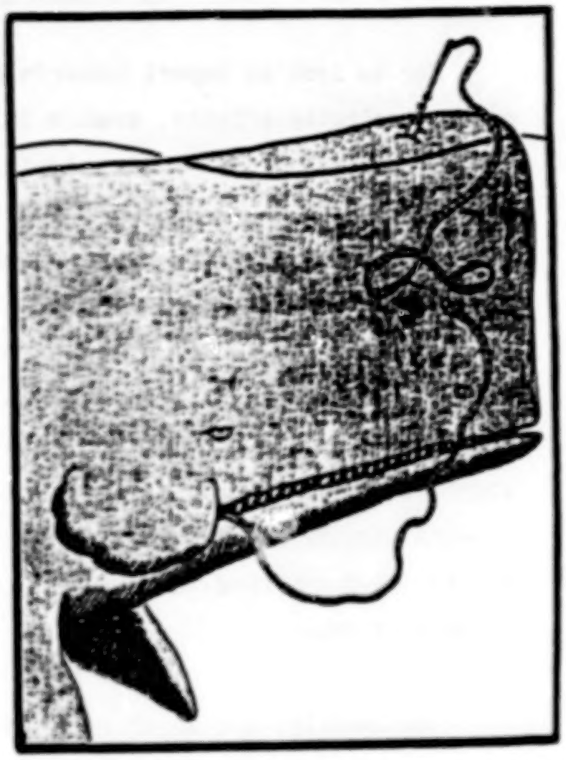
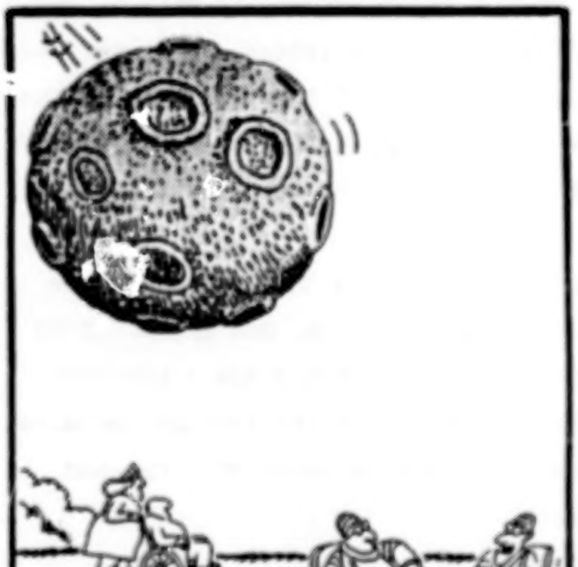




"You're kidding! . . . I was struck twice by lightning too!"

**Very large
meteoroids
are rare;
small ones
are not!**

Now to look at impact hazards more carefully, it turns out that because of hypervelocity effects, even a fairly small particle--1/3 the diameter of the tether--can cause fairly significant damage. And the problem is not just that gods throw rocks--in addition to that, we leave debris in space. When you start looking at the debris problem, you realize that the effective area of a tether for collision with objects much wider than the tether is really the length of the tether, times the width of the DEBRIS. The major debris risk to tethers seems to be associated mainly with the few hundred largest objects, whose combined width is several kilometers. When you take that width, times the length of a tether, times the average relative velocity of objects passing each other in low orbit, which is about ten kilometers per second, then you find that tethers can be effectively sweeping out very large volumes of space.

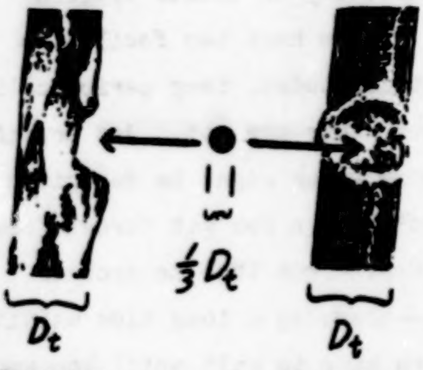
Now luckily, the worst risk is above the proposed space station altitude--the densest region is 600 to 1100 kilometers. But if you want to have a long tether deployed permanently above the space station, figure on it getting cut about every 1,000 kilometer-years. If it's a 100-km tether, it will be cut once every 10 years, on the average. If it's a 500 km tether, then every two years, on the average. And this risk is independent of the thickness of the tether. It can be many cm in diameter--thick enough that the probability of failure due to meteoroids is low--but still, impact with debris will cut it.

In the lower right corner of the viewgraph, we see the space elevator concept. The main debris hazard is in the lowest 4000 km, and again, it is primarily between 600 and 1100 km. And it turns out that a space elevator like this will be cut a little more than once a year on the average, because the total width of the stuff that can cut it is on the order of 5 km--and that's only the current debris population.

So micrometeoroids and debris are important issues.

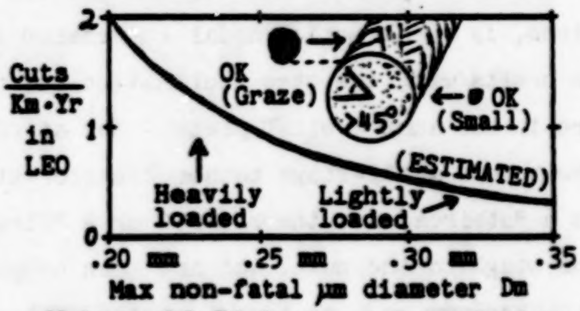
C-2

Impact Hazards for Tethers



Braided Kevlar, grazed

Stainless steel wire, direct hit

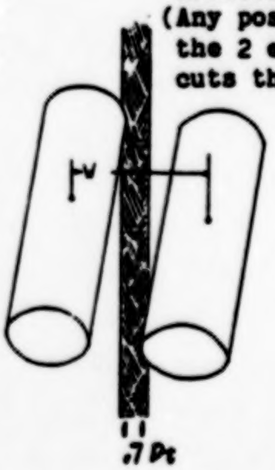


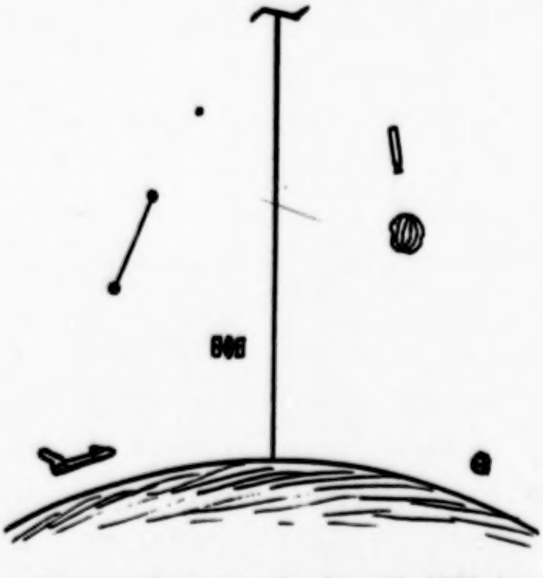
µMeteoroid Risks to a 1 mm Tether

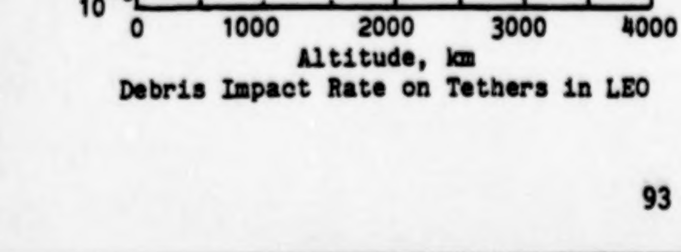
For tethers with Dt > 1 (mm),
& Max non-fatal Dm ≈ .25 Dt,

$$\frac{\mu m \text{ cuts}}{\text{Km} \cdot \text{Yr}} \approx \text{Dt}^{-2.6}$$

Effective Width, W
(Any position between the 2 extremes shown cuts the tether.)







Debris Impact Rate on Tethers in LEO

Debris Risk to the Lowest 4000 km of an Earth-based Space Elevator:

$$\text{Risk} = \frac{\Sigma\text{Width} * \bar{V} * \text{RelDensity at } \lambda{=}0}{\text{Earth "Surface Area" at Alt}}$$

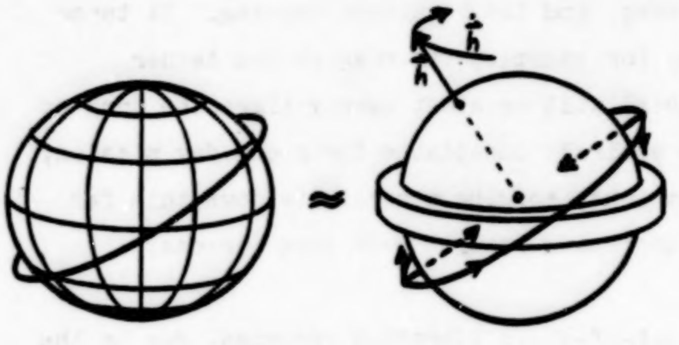
$$= \frac{\sim 5 \text{ km} * \sim 7.3 \text{ km/sec} * \sim .72}{4 * \text{pi} * \text{Sqr}(\sim 7378 \text{ km})}$$

$$\approx 3.9\text{E-}8/\text{sec} \approx \boxed{1.2 \text{ cuts/year}}$$

Another entirely different sort of issue which, again, has nothing to do with tether dynamics per se, but affects the feasibility of tether applications, is differential nodal regression in LEO. If you have two facilities in orbits with the same inclination but different altitudes, they periodically are in the same orbital plane. But at other times, they are not. And so, if you have a multi-stage tether transportation scheme which might be described as a "staircase to the stars," or a "fire brigade", where you get thrown from one stage to the next, and are then caught and thrown from that to another one, you may end up—to change the analogy again—spending a long time waiting for the bus in between steps. This is because you have to wait until you and the next stage have regressed into the same plane. Thus you may spend years getting from LEO to GEO. And those years happen to be in the Van Allen belts, which are not a nice place to be.

So one has to look at these constraints.

Orbital Perturbations



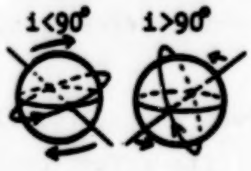
$\dot{h}$
h
$\approx$

OBLATENESS CAUSES LARGE SECULAR CHANGES IN Ω & ω:

$\dot{\Omega}$: up to 1 rad/week in LEO

$\dot{\omega}$: up to 2 rad/week in LEO

Nodal Regression in LEO:

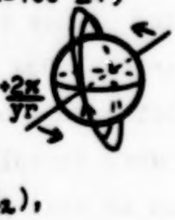


$$\dot{\Omega} \approx \frac{-63.6 \cos i \text{ rad/yr}}{(a/re)^{3.5}\ (1-e^2)^2}$$

$(r_e = 6378 \text{ km})$

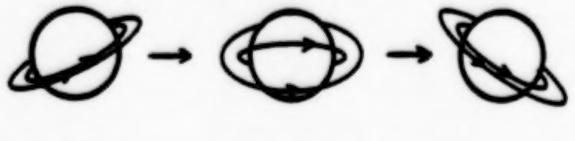
For sun-synchronous orbits: $(i \approx 100° \pm 4°)$

$$\cos i \approx -.0988(a/r_e)^{3.5}(1-e^2)^2$$



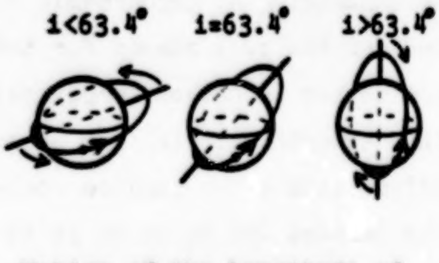
For coplanar low-ΔV rendezvous between 2 objects $(e_1 \approx e_2 \approx 0,\ i_1 = i_2)$, nodal coincidence intervals are:

$$\Delta t_{nc} \approx \frac{180\ (\bar{a}/re)^{4.5}}{\Delta a\ |\cos i|} \text{ km·yrs}$$



Apsidal recession in LEO:

$$\dot{\omega} \approx \frac{63.6(2 - 2.5 \sin^2 i)}{(a/r_e)^{3.5}\ (1-e^2)^2} \text{ rad/yr}$$

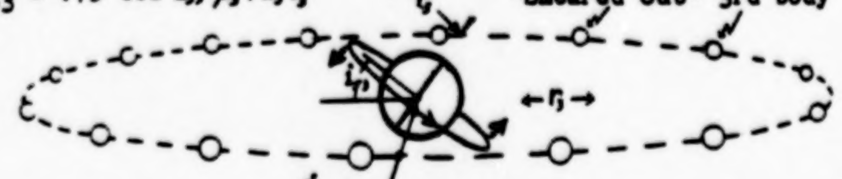


i<63.4°
i=63.4°
i>63.4°

Motion of the longitude of perigee with respect to the sun's direction ("noon") is:

$$\bar{\dot{\omega}}_s = \dot{\omega} + \dot{\Omega} - 2\pi/\text{yr}$$

$$\dot{\Omega}_{s3} = -.75 \cos i_{s3}\ \mu_3 / n_s r_3^3$$



r_3
"Smeared out" 3rd body
i_{s3}
$\leftarrow r_3 \rightarrow$
$\dot{\Omega}_{s3}$

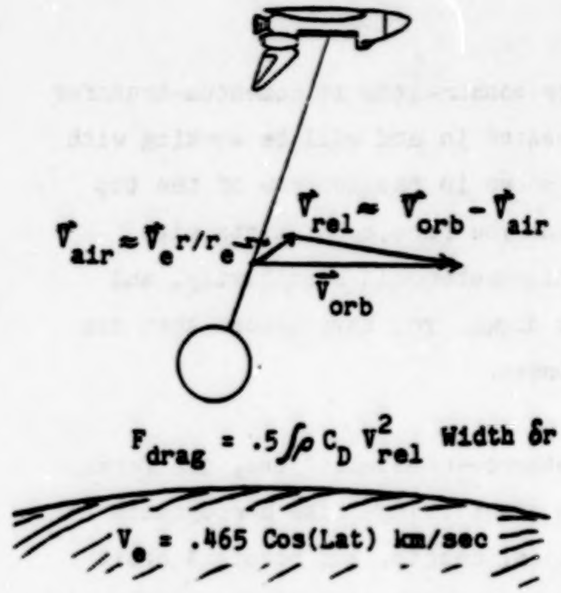
Third-Body Perturbations (non-resonant orbits)

Another issue is aerodynamic drag, and the resultant heating. It turns out that on the tethered satellite, for example, the drag on the tether (mainly on the bottom 10 km of tether) will be about twenty times the drag on the satellite itself. Now this is entirely acceptable for a one-day mission, but for space-station-based applications, hanging a satellite down this far would have a very large effect on the space station over long periods.

The resulting drag can cause out-of-plane libration dynamics, due to the equatorial bulge in the atmosphere and the out-of-plane drag component due to the atmosphere's rotation with the earth. And low altitudes also increase the tether's exposure to atomic oxygen, which degrades most tether materials.

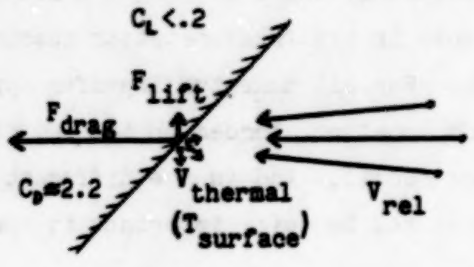
Aerodynamic drag is also important in an entirely different way. An understanding of aerodynamic drag and its effect on orbital life is important because the main reason for boosting objects into higher orbits in LEO is to reduce the amount of aerodynamic drag. Since tethers tend to boost objects into eccentric orbis, the question arises: How do I compare the tether boost effect with a two-impulse rocket boost into a circular orbit? Well, probably the fairest way to do so is to find what circular orbit gives the same orbital life as a given eccentric orbit. And so that requires an understanding of aerodynamic drag and orbital decay.

Aerodynamic Drag


$\vec{V}_{rel} \approx \vec{V}_{orb} - \vec{V}_{air}$
$\vec{V}_{air} \approx \vec{V}_e r/r_e$
$\vec{V}_{orb}$

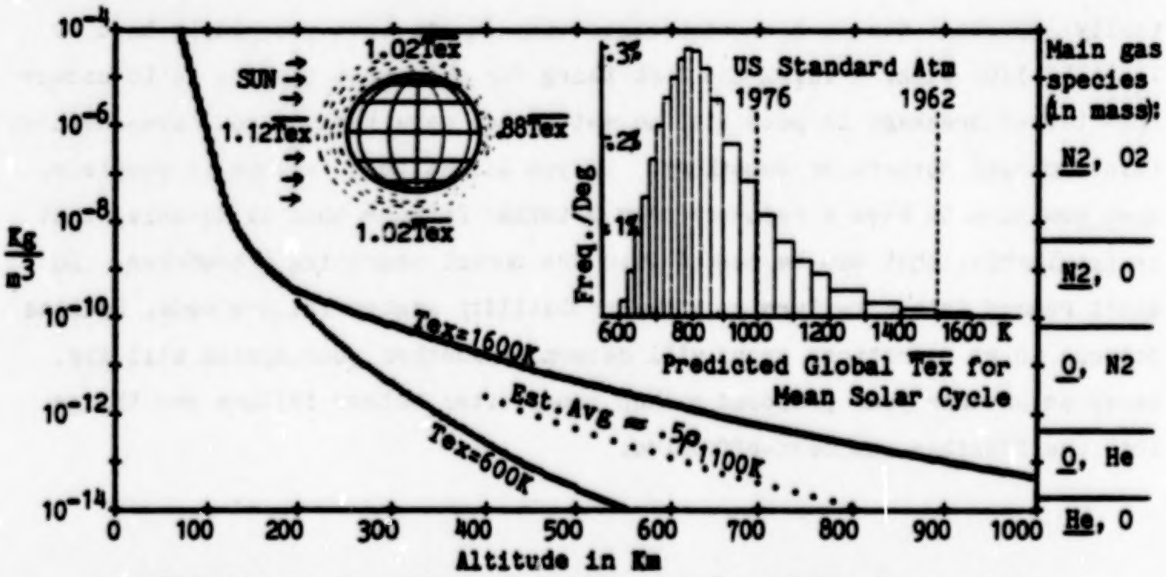
$F_{drag} = .5 \int \rho\, C_D\, V_{rel}^2$ Width δr

$V_e = .465\ \mathrm{Cos(Lat)}$ km/sec


$C_L < .2$
F_{lift}
F_{drag}
$C_D \approx 2.2$
$V_{thermal}$
$(T_{surface})$
V_{rel}

Lift & Drag in Free-Molecular Flow

$(\bar{\lambda} \gg D_{tether};\ \bar{\lambda} \approx \frac{10^{-7}\ \mathrm{kg/m^2}}{\rho})$



Air Density as Function of Altitude & Exosphere Temperature

70<Alt<118:	$\rho \approx 11\exp(-\mathrm{Alt}/6)$	$-\rho/\dot{\rho} = H = 6$ (km)
118<Alt<200:	$\rho \approx (\mathrm{Alt}-95)^{-7}/2600$	$H = (\mathrm{Alt}-95)/3$
200<Alt & ρ>1E-14:	$\rho \approx \frac{1.47\mathrm{E}{-16}\ \mathrm{Tex}(3000-\mathrm{Tex})}{(1+2.9(\mathrm{Alt}-200)/\mathrm{Tex})^{10}}$	$H = .1(\mathrm{Alt}-200)+\mathrm{Tex}/29$

$$\text{Circular Orbit Life} \approx \frac{.15\ \mathrm{m^2 yr}}{\mathrm{kg}}\ \frac{M}{C_D A}\ \frac{(1 + 2.9(r-6578)/\mathrm{Tex})^{11}}{3000 - \mathrm{Tex}}$$

$(-14 < \mathrm{Log}\,\rho < -10)$

$$\text{Equal-Life Circ. Alt.} \approx \text{Perigee} + \frac{\text{Apo} - \text{Per}}{2 + .154(\text{Apo}-\text{Per})/H_{Per}}$$

Now, to put this all together, the major constraints in momentum-transfer applications, which is what I'm mainly interested in and will be working with the most in the transportation session, are shown in the top row of the top table. For all momentum transfer applications you face constraints with apside location, forces on the end masses, micrometeoroid sensitivity, and tether recoil. And in the different subsets shown, you have issues that can crop up and be quite important in specific cases.

When you look at permanently dployed tethers--constellations, platforms, and things like that--you have to worry more about things like aerodynamic drag, libration, tether degradation, meteoroids, debris, and recoil & orbit changes after a tether break. Looking at tether operational issues, which are really important due to the constraints they impose that you simply have to learn to live with, I think the best thing for the space station is to assume that tether breakage is possible, no matter how many backups you have--such as five separate tethers or something. If you assume that failure is possible, then you have to have a recovery from a tether failure that is do-able, that is imaginable, that can be costed into the normal operating procedures. So don't regard tether failure as a low-probability system failure mode, because someone in an operations group will determine whether your system will fly, based on whether your proposed backup modes after tether failure are things that are feasible and cost-effective.

Generic Issues in Various Tether Applications

MAJOR CONSTRAINTS IN MOMENTUM-TRANSFER APPLICATIONS

CONSTRAINT: APPLICATION:	ORBIT BASICS	TETHER DYNAMICS	TETHER PROPERTIES	TETHER OPERATIONS
All types	Apside location	Forces on end masses	µmeteoroid sensitivity	Tether recoil at release
Librating		Tether can go slack		Facility attitude & "g"s variable
Spinning		High loads on payload		Retrieval can be difficult
Winching		High loads on payload		Extremely high power needed
Rendezvous	Orbit planes must match			Short launch & capture windows
Multi-stage	Dif. nodal regression			Waiting time between stages
High deltaV	Gravity losses	Control of dynamics	Tether mass & lifetime	Retrieval energy; Facility Δ alt.

MAJOR CONSTRAINTS WITH PERMANENTLY-DEPLOYED TETHERS

CONSTRAINTS: APPLICATION:	ORBIT BASICS	TETHER DYNAMICS	TETHER PROPERTIES	TETHER OPERATIONS
All types	Aero. drag	Libration	Degradation, µmeteoroids & debris impact.	Recoil & orbit changes after tether break
Electrodynamic	Misc changes in orbit	Plasma disturbances	High-voltage insulation	
Aerodynamic	Tether drag & heating			
Beanstalk (Earth)			Tether mass; debris impact	Consequences of failure
Gravity Use: Hanging Spinning		Libr-sensitive		<.1 gee only. Docking awkward

Now, I'd like to summarize and end with a couple of images, since the senator who just spoke referred to the importance of imagination. One is that Professor Colombo, at his banquet speech two years ago in Williamsburg, talked about a group which I would like to learn more about: the "imagineers"--the people who are engineers, but who have flights of fancy that they turn into practice. I think that we have to have analytical skills among us. And what we don't already have individually, we have to acquire by sitting with the right people at lunch and at dinner, so that we can do the ten-dimensional analysis of this one-dimensional physical structure.

But we also have to have imagination. And here's an example of the sort of menagerie, or zoo, of applications that one can imagine using animal analogues.

First, the TSS is like a spider: it goes down and can go back up on a string. Next, the space station might be configured like an animal that has its eyes on long stalks, because that has advantages in some cases. A space station may not be as clean as one would like, since it will be working with the shuttle and OMV and OTV. So putting the eyes of the space station--the astrophysical eyes--out on the ends of long tethers may be beneficial to both the eyes and the space station, by allowing them to play their individual roles with less interference. Another analogy is that the STS can act like a fish biting a baited hook. Or if the active object is an OMV at the end of the tether, the OMV can act like a chained dog and bite the ET on the nose to capture the shuttle.

A "monkey" can climb along tethers and other structures, and can free-fall from one structure to another merely by letting go at the right place. This is a way of getting around, not just in a forest on earth, but also in a forest or parade or large advanced infrastructure in LEO. The next image is of a water-skimming bird picking up small payloads: there is a possibility of doing some ram air-collection in the future--30 or 40 years from now perhaps. And then, for ambitious developments on the moon, you can be in lunar orbit and reach down and pick small objects off the surface, using a swinging or spinning tether much like an elephant uses its trunk. You can do prospecting over the whole moon with one facility in lunar polar orbit.

I think may be useful to send our imaginations back to the birth of sailing, and remember that the people who were developing sailing technology did not know the thousands of ways in which ropes would end up being useful. They worked on them a few at a time. And perhaps over the next 1,000 years, we will find as many uses for ropes in space as Venetians found for ropes on sailing ships.

I would like to end with a rather amusing image, that I think will bring home a point powerfully. And that is a cartoon which I saw recently. It shows a young lady, standing, and a young man, standing on her head. And he is saying to her, "Well, we've taken our clothes off, and I've gotten on top of you, but somehow I think we are doing something wrong. It doesn't feel very good." And she says, "I know what you mean. I'm getting cold, and I think I'm getting a headache."

The point--the relevant point here--is that, when you hear about something entirely new and different from anything you've ever done before, make sure you learn the relevant facts of life--because otherwise you will not only not do it right, but you may not ever even realize what a good thing it was that you were missing out on.

So what we need to do in the next three days--and over the next 10 years--is to literally lose our technological and engineering innocence, so that we can go home with something a lot better than a cold and a headache.

• • • • • • • • •

CARROLL: Now I would like to introduce Professor Silvio Bergamaschi, from the University of Padua. He is going to talk in far more detail about one of the subjects I have mentioned. Realistically, for a good introduction to tether fundamentals, we need to have ten such talks, one on each of the many topics that I have touched on. But we are still beginners, and Professor Bergamaschi will introduce us to one of the few fields in which we are now able to make this sort of introduction.

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A REVIEW OF TETHER INDUCED DYNAMICAL FEATURES

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INTRODUCTION

A talk in the general field of tether fundamentals cannot be started without a mention to the S.A.O.report of september 74 {1}where the "Skyhook" (this was the first name given to the TSS) was presented. In fact, as pointed out in {2} and {3}, it is true that tethers in space have been conceived since the last years of the 19-th century, but it is also true that until the 70-s they had been part of more or less visionary concepts. On the contrary, in {1} the idea was put on sound engineering grounds and the compatibility with the Space Shuttle was clearly shown. Consequently, investigations of possible uses of tethers in space were undertaken and in the succeeding years the peculiarities of TSS motion were investigated extensively, so that at present it can be said that, if elastic effects are ignored, TSS dynamics is sufficiently well known. Further, it can also be said that the experience acquired in past and present investigations is sufficient to allow the simulation of the motion of more complex tethered systems with a reasonable degree of accuracy.

SOME FEATURES OF TETHER DYNAMICS

In order to make a review of the most peculiar features of tether dynamics let us consider the simplest mathematical model having been used for the simulation of TSS motion. However, as it will appear from the assumptions below, the same model is also useful to investigate a larger class of tethered platforms.

In fact, most of the systems proposed so far for future applications have mechanical features (mass, inertia moments, orbit) and operational requirements which are largely different from those of the first satellite, but the relevant environmental forces (gravity gradient, Coriolis during manoeuvres, eccentricity excitation, etc.) will be the same.

Let us assume that:

- the system is composed by a massive main body (space station or other) in circular orbit and by a smaller platform connected to it by means of a variable length tether; moreover, the mass of the tether is negligible;
- the Earth is spherical and homogenous, so that oblateness and higher order gravitational perturbations are ignored;
- non gravitational forces, as aerodynamic drag or other elasticity effects are very small so that they can be neglected;
- the platform is a point mass.

In this case, it is well known that the system has two stable equilibrium configurations, aligned with the local vertical, so that the classical methods of mechanical vibrations can be used to investigate the motion of the platform in the neighbourhood of them. Therefore, if the gravitational energy is reduced to a quadratic form with respect to the ratio ℓ/a of the tether length to the semimajor axis of the station orbit and if the small amplitude approximation is also made, the dynamical equations can be written as:

$$\ddot{\theta} + 2\frac{\dot{\ell}}{\ell}\theta + 3n^2\theta = -2n\frac{\dot{\ell}}{\ell} \qquad (1)$$

$$\ddot{\phi} + 2\frac{\dot{\ell}}{\ell}\phi + 4n^2\phi = 0 \qquad (2)$$

where:

- **θ is the offset angle from local vertical in the orbit plane**
- **ϕ is the out of plane offset angle**
- **n is the orbit mean motion**
- **the dots mean differentiation with respect to time.**

First, let us consider station keeping conditions, where tether length is constant. From (1) and (2) it is immediate to verify that motion is stable, consisting of two uncoupled librations with constant amplitudes. It can be seen from fig.1 that tether periods are slowly increasing functions of the altitude h.

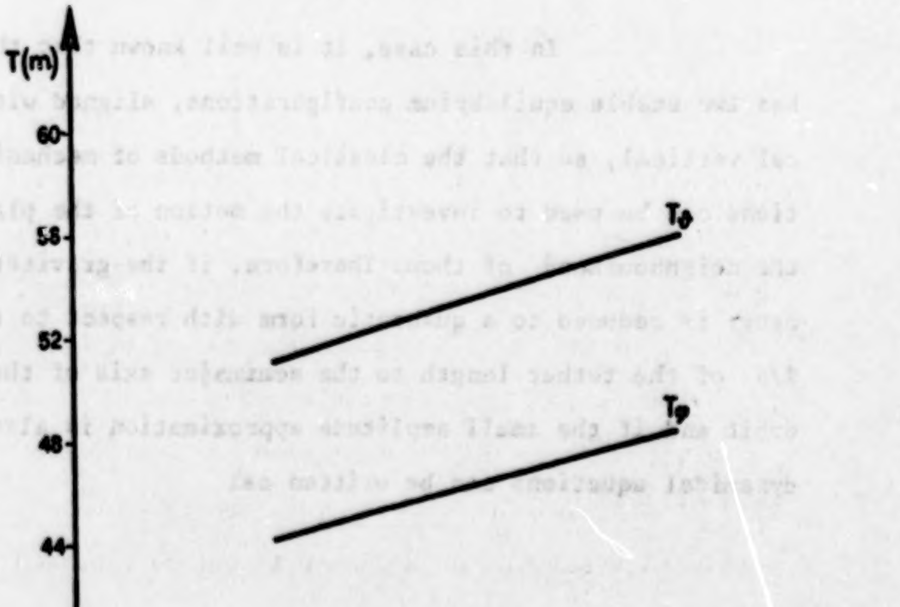

FIG. 1. -

If tether length is not constant in time, as during deployment and retrieval, the terms proportional to $\dot{\ell}$ in eqs.(1) and (2) are different from zero. First, let us consider the last (forcing) term in the θ equation; its structure suggests that it is originated by the Coriolis force which pushes the platform away from the local vertical. In plane instability can occur during the first phase of deployment and the last of retrieval; if the same control law for ℓ is used in the two phases, they are equally critical. The asymmetry between deployment and retrieval is apparent from the velocity dependent terms in both the equations: it is seen that when the coefficients are positive (i.e.during deployment) librations are damped by length increase, on the contrary, during retrieval self excited librations can occur, so that the most critical situation is encountered in the last phase of retrieval.

ELASTICITY EFFECTS

The considerations made so far have ignored elasticity effects. Unfortunately, (from the point of view of simulation problems), the tether is an elastic continuum, so that it can undergo a variety of vibrations: longitudinal, torsional, lateral (both in plane and out of plane). A preliminary evaluation of the frequencies involved in the TSS case has been made in {4} and {5} and further investigation is currently in progress.The same analysis can be extended to different tethered systems, but since now it can be expected that the frequencies of elastic modes will be much higher than those of pendulum-like librations. This is a well known feature of TSS dynamics; its occurence is the cause of serious difficulties in simulating the motion with purely numerical methods. In fact the integration step must be small enough to allow correct simulation of the short period component of the motion, so that the time needed for a physically meaningful numerical simulation can easily be excessive.

A major problem is the evaluation of the dynamical noise acting on the platform. In fact, one appealing feature of tethered platforms is the possibility of attaining high pointing accuracies by isolating them from the noise originated in the primary. To make an example, Aeritalia has investigated the possibility of actively controlling the motion of the point of attachment of the tether to the SATP (Science and Application Tethered Platform) in order to achieve a pointing accuracy of the order of 1 arcsec in attitude control. In this frame the tether itself can be viewed as a passive damper the efficiency of which must be tested carefully.

This is because at present very scarce information is available even about the properties (in particular about structural damping) of the materials to be possibly used in the first TSS flights. It is expected that post flight analysis of the accelerations at the satellite will provide some informations on tether damping, but the tuning (if possible) of a tether to a given system, in order to maximize energy dissipation, will certainly require further experiments.

One additional problem is the possibility of coupling between the attitude motion of the platform and some of the higher modes of tether lateral vibrations. While coupling can be expected on the basis of approximate modal analysis, a reasonable estimate of vibration amplitudes requires the knowledge of excitation sources and system damping. Again, at present experience is lacking , so that the analysis on TSS will be useful as a first step to understand more complex systems and, in particular, to discriminate between what is really important from what is negligible (at different levels of accuracy).

Perturbation sources

In spite of the problems mentioned above, a preliminary knowledge of the response of a tethered system to most likely perturbations is fundamental, in order to make an evaluation of the order of magnitude of the dynamical noise to which it is expected to be subject.

What follows is a tentative list of the best known mechanical perturbing actions; from the comparison of their dynamical features with system natural frequencies it is possible to have a feeling of their impact on the motion and, consequently, on experiments requirements.

Orbit eccentricity

Nominally, the orbit of the Space Station (S.S.) will be circular, but the actual orbit will be allowed a residual eccentricity e. In a pendulum-like system e affects the in plane motion originating a forced libration with amplitude equal to e and period equal to the orbital period. With $e = 10^{-4}$ and a tether length of 10 Km, the acceleration amplitude would amount to $\simeq 1.2 \cdot 10^{-7}$ g.

Earth oblateness

The well known secular regression of the line of nodes and advance of the apsidal line should not cause major dynamical problems to a tethered system. However, perhaps it is less widely known {6} that Earth oblateness causes both semimajor axis a and inclination i of a circular orbit to undergo variations with periods equal to half the orbit period, i.e. with frequency equal to the out of plane libration frequency. Therefore resonance can occur and vibration amplitudes can increase in time.

The mathematical modelization of this dynamical feature is not simple. At present, it is believed that, due to the relatively short time span of the mission, TSS libration amplitudes cannot grow to undesired levels; however further investigation is needed if longer missions, in connection to the S.S., are envisaged.

Temperature changes

Tether length in the stressed equilibrium configuration parallel to the local vertical depends on temperature. In low altitude, low inclination orbits, space temperature changes by some 10 deg. twice per orbit, so that the possibility exists that longitudinal vibrations be excited during the transition from sunlight to Earth shadow and viceversa.

The maximum acceleration at the platform depends on the coefficient of thermal expansion α of the tether. Testing of candidate materials should take into account also this aspect of the problem; in fact it does not seem impossible, in line of principle, to use a tether with a very small α value.

Internal sources of perturbation

One of the features of platforms tethered to the S.S. is the possibility to act as almost independent subsystems with minimum interference with other S.S.activities. The tether, however can transmit disturbances to the platform; in this way noise can be originated by Shuttle docking, station keeping manoeuvres, crew motion, etc.

At present, no reliable estimate is possible of the dynamical noise at the platform, because of lack of information on tether damping properties. In this concern,as mentioned before, the results of a study about the possibility of using the tether as a structural damper could pay for the effort.

Natural frequencies

From the review above it can be seen that perturbing forces can be categorized into two groups with respect to the frequency of the excitation. Long period forces are those with frequencies comparable to the mean motion (eccentricity and Earth oblateness effects) while short period forces are those with much higher frequencies (at least one order of magnitude). The former ones are not likely to excite tether elastic modes, while the latter, on the contrary, can do that. This is the reason why a numerical example of the frequencies possibly involved is presented below in a study case.

Let us assume that the orbit is circular at 500 Km height and that the platform mass is m:5*10^4 Kg. Also, the tether parameters are:

$\rho = 1.5$ Kg/m^2 mass density
$\mu = 0.5$ Kg/m mass per unit length
E = 7*10^{10} N/m^2 Young modulus

Longitudinal vibrations

If it is assumed that the tether end at the S.S. is fixed and that, at the platform, the inertia force must be balanced by the elastic stress, approximate values of the periods of the first longitudinal vibration modes can easily be found {7}.

The first ~~five~~ periods are reported in Tab.1 for two different tether lengths.

T(sec) \ ℓ(Km)	1	10
T 1	9.2	29.5
T 2	0.29	2.9
T 3	0.15	1.5
T 4	0.10	0.98
T 5	0.07	0.7

TAB. 1. -

Lateral vibrations

The same approach can be adopted for lateral vibrations. The main difference is that in the fundamental modes elasticity is not relevant and that in plane and out of plane librations have different periods. On the contary, elastic effects are dominant in upper modes, so that higher frequencies are almost coincident. For this reason, only the periods from T 2 to T 5 are reported in Tab.2.

T(sec) \ ℓ(Km)	1	10
T 2	141	306
T 3	70	156
T 4	47	105
T 5	35	79

TAB. 2. -

Torsional vibrations

Torsional vibrations are believed to have a minor impact on the overall noise, because of the very large ratio between platform yaw moment of inertia and tether inertia. Only the torsional spring mass mode could be excited by disturbances originated in the platform itself. No evaluation is made of the corresponding period because of the uncertainty of the parameters involved.

The period of the upper modes is, however, in the range of 1 sec or less for both the lengths.

Platform attitude motion

The evaluations of the periods is quite uncertain, because of the large variability range of the parameters involved. However, let us assume that the distance of the platform c.o.g. from the tether attachment point be equal to 5 m and that the radius of gyration both in pitch and in roll be 3 m. The periods are shown in Fig.2 vs.tether length.

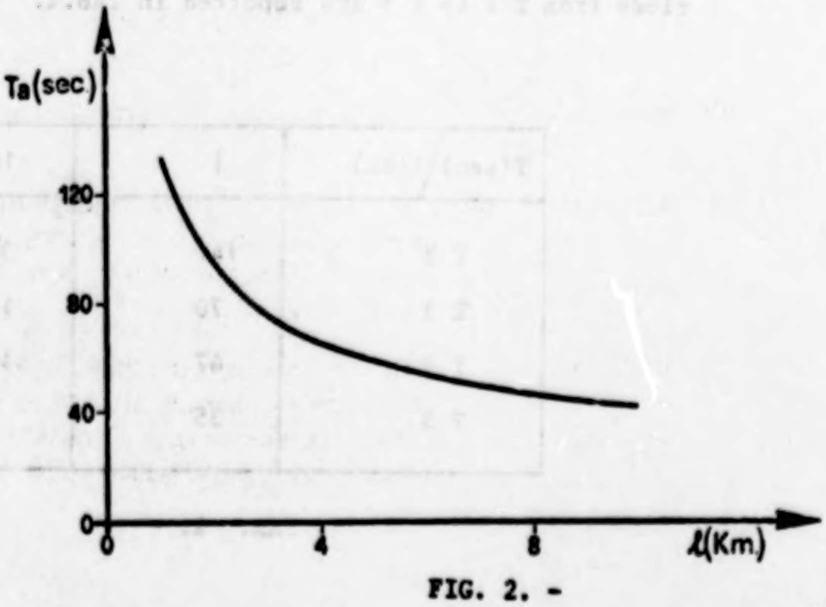

FIG. 2. -

CONCLUSIONS

Tethered systems provide a very interesting and, in some sense, unique opportunity for scientic activity in space. Some of the experiments envisaged so far, however, require the measurement of very small mechanical quantities (accelerations etc.). This implies that the level of dynamical noise on instruments output be low or that system response to excitations, either external or internal, be sufficiently known.

In this respect, the first TSS flights will be very useful, but much work will be needed in order to have reliable estimates of structural damping in different future systems.

REFERENCES

{1} Colombo,G.et al. "Shuttle-borne "Skyhook": A New Tool for Low-Orbital-Altitude Research". S.A.O.Report,Sept.1974.

{2} Tiesenhausen (Von),G. "Tethers in Space.Birth and Growth of a New Avenue to Space Utilization". NASA TR-82571 MSFC,Feb.1984

{3} Bekey,I. "Applications of Space Tethers".I.A.F.Paper 84-436.

{4} Bergamaschi,S. "A Theoretical and Experimental Investigation on TSS Dynamics". Proposal in response to NASA-CNR/PSN AO.n.OSSA 1 -84 , July 1984.

{5} Gullahorn,G. "Investigation and Measurement of Dynamic Noise in Tethered Satellite Systems".Proposal in response to NASA-CNR/PSN AO. n. OSSA 1-84, July 1984.

{6} Sterne,T.E. "An Introduction to Celestial Mechanics". Interscience Tracts on Physics and Astronomy.,1960, Ch.5.2.

{7} Volterra,E.,Zachmanoglou,E.C. "Dynamics of Vibrations". Merrill Books,1965, Ch.4.3 .

N86-28412

SCIENCE APPLICATIONS

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1 GENERAL.

The possibility of doing science by tethers and/or tethered vehicles is now in the process of becoming a reality in the next few years.

Following early qualitative suggestions and studies, a serious start of quantitative studies is due to G.Colombo and M.Grossi, who in the early 1970's suggested to tether satellites to the Shuttle by means of long strings up to a length of 100 km.

A cooperative program was estabilished in the following years between USA and Italy, until in 1983 a M.O.U. was signed by the two countries; this was followed in 1984 by an A.O. stating that NASA and PSN/CNR "jointly announce an opportunity for partecipation in the first three flights of the Tethered Satellite System (TSS) on the Space Shuttle. These flights are expected to occur between 1987 and 1990. The TSS is comprised of two major elements, the Deployer, to be supplied by NASA, and the Satellite, to be provided by PSN/CNR. In addition, it is the intention of NASA and PSN/CNR to supply two items of core equipment for these flights; a three-axis accelerometer, placed on-board the Satellite, and an electron gun, to be mounted on the Deployer. Science instrumentation can be accommodated on both the Deployer and the Satellite".

Theoretical and experimental proposals for the definition and development of investigations for the first three flights and for analysis and interpretation of data were solicited. The answer by the scientific community was very encouranging: about 80 proposals were presented, approximately 1/5 from Europe and Italy in particular, 4/5 from USA and non-european countries.

It is my intention in this presentation, to summarize possible scientific applications in the field of the neutral or ionized atmosphere and of the solid Earth. As concerns the field of electrodynamic interactions, it will be the subject of another presentation so, here, I shall only list as an appendix a summary of the satellite and deployer scientific instrumentation selected for the first mission (the electrodynamic mission).

It is very important to remark that the TSS environment is a sort of huge laboratory where many different physical parameters influence each other in a very complicate way, under the external influences of the solar EUV radiation and the magnetospheric particles and the internal influence of the terrestrial gravity and magnetic field. It is worth to point out that while the interpretation of data from some types of experiments does not require a very precise determination of the geographic coordinates of the TSS-satellite, in other cases there are very stringent precision requirements, to the point that these may be the absolutely essential feature before significant physical interpretation can be attempted; this is the case of all parameters defined in a reference system anchored to the solid earth (gravity and geomagnetic field).

In this respect the study of TSS dynamics is interesting and useful "per se" because of the novelty of the system and the related need of better understanding. But from the view point of other experiments, the TSS dynamics is also inherently related to the possibility of measuring fine quantities. For example doubts have been expressed about the feasibility of gravity gradient measurements because "the dynamic noise expected in a tethered satellite is far higher than in a free flyer and may negate the advantages of flying at this unusually low orbital height". This same comment also applies to geomagnetic field measurements.

2 NEUTRAL ATMOSPHERIC MOTIONS AND COMPOSITION.

To study vertical, zonal and meridional neutral winds and temperature, whose extensive variations suggest importance of energy transfer mechanism in modifying the structural properties of the region. Thermospheric circulation models suggest existence of horizontal scale vortices generated by auroral processes at high latitudes, between 120 and 200 km altitude.

In this region, minor neutral constituents generated by auroral and solar particles are conveyed to other atmospheric regions by the winds. Also, the distribution mechanism of the EUV energy is an important goal. The EUV energy flux is relatively small ($\approx$1eV/cm /sec), but the gas density also is small, so large effects are produced by this energy source. Another energy flux reaches the upper atmosphere from the solar wind and the ionization through the magnetosphere, in the form of precipitating particles. This effect is dominant at high latitudes, but global effects can also be observed during geomagnetic disturbances. Electric currents and ion drifts transfer energy and momentum to neutrals, producing winds at velocity of 1 km/sec.

Energy of tidal motions can also propagate from lower atmosphere to the thermosphere where it is finally dissipated. In this region also important ionospheric effects are generated by the wind system (S_q dynamo currents, electrojects, etc.).

All above processes strongly affect the composition and the thermal and dynamic regime of the neutral atmosphere, in the range from 100 to 200 km altitudes where only a few *in-situ* observational data do exist.

A major factor which may limit the accuracy or even the feasibility of in-situ measurements by hypersonic vehicles at TSS low altitudes is represented by the collisions suffered by free stream neutrals and ions as they pass through the ram cloud ahead of the satellite.

Also important is the ionization produced by neutrals impacting the exposed surface of the s/c and the instrument sensors.

3 IONOSPHERIC ELECTRON AND ION COMPOSITION. IRREGULARITIES AND DISTURBANCES.

Below the F region, "intermediate layers" of high plasma density are often observed. These layers propagate to lower altitudes with drift velocities of the order of 20 m/sec. Composition and motion of this layers are important parameters to be measured by the TSS, in order to understand their phenomenology, also in conjunction with ground-based radar observations. A variety of plasma structures at different spatial and temporal scales in the lower F region will be studied.

Local measurements of electron densities and temperatures, as well as of d.c. electric fields and ionospheric current will contribute basic informations on the overall energy balance.

Large and medium scale travelling ionospheric disturbances will also be studied. These disturbances have typical wavelengths of some thousands km and can propagate from high to equatorial latitudes. Also, acoustic-gravity waves generated in the E region, which might be the source of the spread-F, will be possibly observed.

A number of metallic ions (Na , Mg , Si , Fe , etc) are mixed to the most commom ions. Some of them are long-lived and can be transported by both neutral winds and electric field. Ion composition measurements will help to sort out the most important ion sources and to determine the role played by meteoritic ions.

4 FLUIDODYNAMICS.

Basic fluidodynamics problems can be studied onboard tethered satellites. In particular, aerodynamic and heat transfer coefficients within a variety of conditions which cannot be obtained by the current wind tunnel technology, due to the impossibility of making thermo-fluid-dynamic measurements at combined low Reynold number and large Mach number regime. An additional advantage of using the TSS as "open wind tunnel" is the long time range of operation, as compared with any existing or proposed ground facility.

5 MAGNETIC FIELDS.

The magnetic field at TSS altitudes is the sum of fields from different sources: the global geomagnetic field of internal origin, the field due to anomalies of limited extent associated with permanently magnetized subsurface structures, ionospheric currents driven by large scale atmospheric motions or originating in the magnetosphere and, finally, the induced electric current flowing along the tether (in the case it is conducting).

Separation of the different contributions may become a formidable task unless the dynamics of the tethered satellite (location and attitude) is perfectly known and any possible spurious field from the s/c is below the magnetic sensors sensitivity.

Studies will be conducted on the structure of the equatorial electrojet, in particular its longitudinal and meridional extent. Also, the closure of the current loop as a whole will be studied. Toroidal magnetic field structures, not observable from ground, have been suggested, which can only be detected by in-situ measurements.

The S_q diurnal field variation will also be observed and the induced effects on the Earth will be possibly determined in a more direct way by comparison with ground observations.

Crustal field anomalies will be detectable, hopefully, expecially for the lower altitudes flights.

Magnetic measurements will also be used to probe the tether current distribution in the plasma sheath around the s/c, as a necessary complement to the local plasma parameters determinations.

6 GRAVITY ENVIRONMENT.

Exact knowledge of the Earth's gravitational field is important in many technical and scientific areas (Earth resources, oceanphysics, motions of tectonic plates, inertial navigation, etc.). The low altitude TSS missions will be useful to this end, if the dynamics of the tethered satellite will be sufficiently well known to determine gravity gradients with the required, high, accuracy. Studies presently in progress seem to indicate good chances of flying gravimetric gradient instruments in the following missions.

7 REMOTE SENSING.

The TSS facility for remote sensing purposes may prove useful to increase significantly the accuracy of future real time cartographic systems from space. In this framework, two operational missions have been suggested: one using two linear array systems for along-track stereoscopic observation; the other using a synthetic aperture radar combined with an interferometric tecnique. Feasibility studies are presently in progress.

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APPENDIX

SCIENCE FOR THE FIRST TSS ELECTRODYNAMIC MISSION

SCIENTIFIC OBJECTIVES

- STUDY OF ELECTRODYNAMIC INTERACTION BETWEEN THE TSS AND AMBIENT PLASMA
- STUDY OF DYNAMICAL FORCES ACTING ON THE TETHERED SATELLITE

SATELLITE INSTRUMENTATION (and P.I.'s)

- RESEARCH ON ELECTRODYNAMIC TETHER EFFECTS (RETE) - M. DOBROWOLNY CNR/IFSI - FRASCATI - ROME
  WAVE SENSORS ON TWO EXTENDABLE BOOMS (4 m EACH) TO EXPLORE SPACE CHARGE REGION AROUND SATELLITE.
- TETHER MAGNETIC FIELD MEASUREMENT (TEMAG) - F. MARIANI - 2ND UNIVERSITY OF ROME - TOR VERGATA - ROME
  TWO MAGNETOMETERS ON FIXED BOOM (85 cm) TO MEASURE MAGNETIC FIELD AND DYNAMICS OF TETHERED SATELLITE.
- RESEARCH ON ORBITAL PLASMA - ELECTRODYNAMICS (ROPE) N. STONE - NASA/MSFC HUNTSVILLE - ALABAMA
  PARTICLE SENSORS ON FIXED BOOM (85 cm) AND ON SATELLITE TO STUDY SATELLITE PLASMA INTERACTION.

DEPLOYER INSTRUMENTATION

- SHUTTLE ELECTRODYNAMIC TETHER SYSTEM (SETS) - P. BANKS - STANFORD UNIVERSITY - STANFORD - CALIFORNIA
  VARIOUS INSTRUMENTS TO STUDY TETHER CURRENT - VOLTAGE CHARACTERISTICS, CHARGE CONTROL AND EMISSION AT ORBITER, OTHER PLASMA AND IONOSPHERIC PROCESSES.

THEORY AND GROUND-BASED OBSERVATIONS

- THEORY AND MODELING IN SUPPORT OF TETHER - K. PAPADOPOULOS - SCIENCE APPLICATIONS, INC. - McLEAN - VIRGINIA
- INVESTIGATION ON TSS DYNAMICS S. BERGAMASCHI - UNIVERSITY OF PADOVA PADOVA
- INVESTIGATION AND MEASUREMENT OF DYNAMIC NOISE IN TSS - G. GULLAHORN - SAO CAMBRIDGE - MASSACHUSSETS
- DETECTION OF ELECTRODYNAMIC ULF/ELF EMISSIONS BY THE TETHER - G. TACCONI UNIVERSITY OF GENOVA - GENOVA
- INVESTIGATION OF ELECTRODYNAMIC EMISSIONS BY THE TETHER R. ESTES - SAO CAMBRIDGE MASSACHUSSETS.

ITALY IS RESPONSIBLE FOR THE INTEGRATION OF THE SCIENTIFIC INSTRUMENTATION ON THE SATELLITE

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OF POOR QUALITY

TSS CORE EQUIPMENT
TETHER CURRENT-VOLTAGE CONTROL (TCVC) SYSTEM

PURPOSE

FOR THE ELECTRODYNAMIC MISSIONS THE TCVC SYSTEM WILL SPECIFICALLY ALLOW INVESTIGATION OF THE TSS-S ELECTRICAL POTENTIAL BY CONTROLLING THE CURRENT THAT FLOWS BETWEEN THE SATELLITE AND THE ORBITER THROUGH THE TETHER AS A RESULT OF THE EMF GENERATED (UP TO 5 KV) BY MOTION OF THE TSS THROUGH THE GEOMAGNETIC FIELD
THIS FUNCTION IS FUNDAMENTAL TO THE OPERATION OF THE ELECTRODYNAMIC TETHER AND IS ESSENTIAL FOR THE TSS SCIENTIFIC INVESTIGATIONS.

THREE-AXIS ACCELEROMETER-GYRO SYSTEM

PURPOSE

THE THREE-AXIS ACCELEROMETER-GYRO SYSTEM WILL PROVIDE A HIGHLY ACCURATE ASSESSMENT OF DYNAMIC PERTURBATION TO THE MOTION OF THE TETHERED SATELLITE.
THIS INFORMATION IS REQUIRED TO DETERMINE THE SUITABILITY OF THE TETHERED SATELLITE AS A PLATFORM FOR A VARIETY OF INVESTIGATIONS OF CRUSTAL - INDUCED MAGNETIC AND GRAVITATIONAL EFFECTS.

N86-28413

APPLICATIONS OF TETHERS FOR PLANETARY MISSIONS

Paul Penzo
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Mans reach goes beyond Earth orbit into deep space, and as you know, there has been growing interest in trying to decide what will come beyond the Space Station. In fact, such inquiries are being made today by the National Commission on Space, for example, to decide and to justify, in part, the Space Station itself.

The Space Station in the large sense could be considered to be part of what might eventually be an infrastructure; that is, part of a system of capabilities which will eventually take man back to the moon, and then to Mars and beyond.

What roles can tethers play in deep space? With the current interest in long-term space activities, this question is presently being addressed. In Advanced Programs, we held sort of a one-day workshop with a few people from NASA centers at NASA Headquarters to consider the applications of tethers for planetary missions. The contributors for this one-day workshop are here today, which is very fortunate. I would encourage them to specifically attend the Science Applications Panel and expand on their ideas; the ideas which they contributed to the meeting at NASA Headquarters.

I will start with the Moon and work outwards (Figure 1). At the Moon, one proposal which Giusseppe Colombo proposed was simply an instrument package tethered from a satellite in orbit about the Moon. It would be in a polar orbit so that complete coverage of the Moon could be obtained. The satellite could be at a high and safe altitude, say 300 km. Because of the Sun and Earth perturbations, the lifetime of a lower satellite could be short, perhaps a few months, before it would impact the Moon.

Now the tethered instruments could be as close to the Moon as desired, perhaps a few kilometers, with the satellite remaining in a stable lunar orbit. It may be necessary to adjust the tether length occassionally to prevent impact of the instrument package. This mission would result in high resolution data for gravimetric measurements, gamma ray spectrometer measurements, and so forth.

Now I will move on to something which is much more in the future and this is an idea by Joe Carroll (Figure 2). He'll probably discuss it in a panel session. This idea is to build a sling on the surface of the Moon which would take solar energy, for example, and build up momentum of the sling. Two payloads would be at the tips of the sling and each would be released at a precise time. The payload at each end, assumed to be rocks, would be only ten kilograms. The advantage is that 10kg could be launched every five minutes, amounting to 1,000 tons per year. Once certain amounts were in orbit, they would be collected by a Lunar Orbiting Tether Station (LOTS) (Figure 3).

Half of these rocks would then be loaded into an Aerobraking Ferry Vehicle (AFV), deployed on a tether, spun up, and released to transearth injection. The momentum lost by the station would be recovered by ejecting the other half of these rocks back to the Moon. This allows transportation of lunar material to the Earth without use of propellants. The problem of lunar orbit debris still has to be addressed. At Earth, the AFV aerobrakes into LEO and rendezvous with a Tether and Materials Processing Station (TAMPS). An unloaded AFV is then returned to the Moon to repeat the process.

Now, moving on to Mars (Figure 4), there is a Mars Aeronomy Orbiter (MAO) being planned by NASA. This is different from the Mars Orbiter which is currently planned for launch in the late '80s. The MAO mission would be launched in '94 or '96, and is included in NASA's Solar System Exploration Committee (SSEC) Core Program.

This application would simply use a tether to enhance the planned Mars orbiter. The purpose of the mission itself is to analyze the atmospheric composition and chemistry for one Martian year. The idea of the tether would be to send instruments to lower altitudes periodically for in-situ measurements. That is, a tether, say 200 km in length, would not simply be deployed and left deployed. The instrument package would be deployed periodically, maybe every two months, for a period of a few hours and then retrieved. During deployment, the instrument package would make measurements of the upper atmosphere of Mars at that lower altitude. This would enhance the science benefits that you would get from just the orbiter. Cost, of course, would increase.

In a radically different application, it is proposed that a tether can be attached to an asteroid during a spacecraft flyby and, holding the length of the tether fixed, to cause the spacecraft to rotate around the asteroid at a fixed radius (Figure 5). The tether can then be released and the spacecraft will go off in a different direction.

This is exactly what happens with the gravity assist technique. The gravity of a large body causes the direction of a spacecraft to change thus producing a gravity assist. For example, Voyager 2 flew by Saturn in '81, and will reach Uranus this coming January. It could not have done that without the gravity assist of Saturn. In this application, an asteroid could be chosen which was between Earth and Mars and used essentially in what would be an artificial gravity assist mode.

At launch, then, the total energy would not be necessary. Only the energy to get to the asteroid would be needed. The tether attachment and fly around would provide the gravity assist. The length of the tether need only be one or two kilometers long. You would have to have some means, of course, of flinging the tether and attaching it to the asteroid, and then detaching it after you swing around the asteroid. You would need, according to the velocities that would be required for the fly-by, a material which was two or three times stronger than Kevlar.

That incidently is something that should be considered in general. That is, we talk about Kevlar, and sometimes we restrict our analysis to the strength of Kevlar. In most cases, this is quite appropriate. However, that doesn't mean it should be exclusive. We should also look at possible missions, even in Earth orbit, which may require materials which are stronger than Kevlar. And, as Joe Carroll has said, there are materials which are stronger than Kevlar. This will expand the types of applications that we can look at.

Now, lets go on to artificial gravity. It's possible to have a manned mission to Mars and physiologically require artificial gravity. If that turns out to be the case, how do we get artificial gravity?

We can get it through rotation, and I have shown here in Figure 6 two possible concepts of a transfer vehicle which would go from the Earth to Mars. The concept on the left is based on the planned space station technology. There would be four manned modules two at each end of a rotating beam. Two manned modules are shown at the bottom of the station. The length of the structure from the center of mass, where the solar dynamic power system is located, is 100 meters. Now, you would not rotate the whole system. The solar dynamic power system itself would be despun and pointed to the sun. The part that spins is simply the beam to which two manned modules at each end are attached. This would be a dual spinning system.

Also, in order to service the subsystems, and transfer men and supplies to the modules, an elevator which travels along the rotating beam would be ued. It would carry men to the center hub and also to the other side of the two modules. This system would remain spinning until it reached Mars, and then it could be de-spun with the rocket motor shown below the modules.

It is also possible to rendezvous with this spinning system. There would be a de-spun docking platform off the center hub where docking would occur. Then when the rotating beam aligned with the docking system, it would attach to the rotating system. The men and supplies would then transfer to the rotating beam.

Now the system could be simplified by using a platform, as shown on the right side of Figure 6. The platform for economy could use solar arrays instead of a solar dynamic system. The subsystems are at the center, including the reel mechanism for the tether system. The two manned modules (this is only a two module system), would be extended on a ten kilometer tether and then use a propellant motor, located underneath the manned modules, to spin the total system. The solar panels, however, would be de-spun. This is obviously a much simpler system; a smaller system and less costly. This would, in fact, be a better system for artificial gravity, because now, for Mars gravity, for example, the rotating arm length is three kilometers, not just a hundred meters. The disadvantage of this system is the high spin velocity required, i.e., 125 meters per second, versus 20.

In Figure 6, the rotation rates are given in the tables. For a level of 1-g, the station would rotate once every twenty seconds. This rate is quite fast and may introduce strong Coriolis forces. The tethered platform system on the other hand would rotate roughly once every hundred seconds resulting in considerably lower Coriolis forces.

Now, concentrating on Mars itself, it is possible to use tethers to provide a transportation system for payloads which are coming to the surface from escape, and which are leaving Mars and escaping from Mars itself (Figure 7). This method utilizes the two satellites of Mars; Phobos and Deimos. These satellites, 10-20 km in diameter, are large enough to be considered to be stations in orbit about Mars. At each, tethers could be extended upwards and downwards with the lengths given in Figure 7. At Phobos for example the downward tether is 1160 km, and the upward tether is 940 km as shown on the left. At Deimos, the downward tether is 2960 km and the upward tether is 6100 km.

These are quite long, and it turns out they can weigh a few to many tons. A Kevlar tether, with a diameter of three or four millimeters is quite strong enough to handle 20,000 kg payloads.

To understand how this system would work, consider a payload tethered upward 375 km from a spacecraft in a 400 km altitude orbit. When released, the payload would rise to an altitude 1160 km below

Phobos, and have the right velocity to rendezvous with a hanging tether from Phobos.

To continue the operation, the payload would then have to climb that 1160-kilometer tether to the other side of Phobos and up the 940-km tether. It could then be released and be on an orbit whose altitude is sufficient to reach the lower tip of the 2960 km tether at Deimos. There would be no velocity difference there (or anywhere else) so that no propellants are used at all, except for corrections and rendezvous. When the payload is released at the end of the 6100-km tether at Deimos, it will escape from Mars. A spacecraft which is coming into Mars on an escape trajectory could rendezvous with the 6100-km tether and be brought down to Deimos and then to Phobos, and then to low orbit. The tether mass here, using Kevlar, ranges anywhere from three-tenths of the payload mass to roughly five. This is quite acceptable for a system which is intended to have repeated use. Novel ideas will be needed to construct and maintain this system. Also, we still have the problems which Joe Carroll alluded to, and that is micrometeoroid impact causing the tether to be cut. This can be handled with redundant systems and rapid repair.

There has been considerable study at the Jet Propulsion Laboratory on collecting comet or asteroid samples and returning them to Earth. Of particular interest is a comet sample return. The conventional approach would be to rendezvous with the comet or asteroid and release a lander (Figure 8). The lander would drill for a core sample, return to rendezvous with the oribter, and finally the sample would be brought back to Earth. The cost estimate is $1 billion or more, somewhat like the Viking mission to Mars.

A tether approach would be not to rely on a lander for sample collection but simply to have tethered penetrators which could collect samples. The rendezvous with the comet or asteroid may be very close, such as 50-100m, so that the tether need not be very long. The-tethered penetrator would be ejected from the spacecraft into the comet, and samples would then be returned via the tether to the spacecraft itself.

What could the penetrator look like? First, the penetrator would have enough force to dig into the comet, and the shell of that could remain with the comet (see Figure 9). Holes in the shell would allow material to enter a cup inside the shell. A means other than holes may be devised. After penetration, an explosive charge could force a cap to seal the cup, and blow the cup from the shell. Using rotation to cause tension in the tether, the spacecraft could then reel in the cup (this may be a complex procedure) and store it into a compartment for return to Earth.

Now with several of these penetrator/sampler systems on a spacecraft it is possible to collect samples from different spots on the comet, as opposed to the lander, or to collect samples from other bodies. The lander and penetrator methods are complementary. The lander provides single very deep sample, whereas the penetrator can provide smaller samples from different parts of the comet or asteroid.

Combinations of tether techniques discussed so far may be used in an ambitious main belt asteroid tour and sample return, as shown in Figure 10. Now, I will discuss the fascinating area of electrodynamic tethers at Jupiter (Figure 11).

Jupiter has a strong magnetic field, about twenty times that of Earth. However, distances of Jupiter orbits are also larger, which tend to counterbalance the effects. We know that strong electric fields are present in Jupiter's magnetosphere; because of Io's flux tube, for example. Thus, if electrodynamic tethers work well at Earth, they should work even better at Jupiter. This, of course, has to be shown.

What we can do is make the computations for Jupiter that are made for Earth, and an important parameter is the induced voltage in a conducting wire. In computing this, how does the rapid rotation of Jupiter affect the calculations?

Specifically, this is a question which I wish to throw out to you. With Jupiter's rapid rotation of one revolution per ten hours, it turns out that if you get beyond 2.2 Jupiter radii (1.2 in altitude) the magnetic field is rotating faster than the satellite. If that is the case, then Jupiter's magnetic field is rotating faster than a satellite in circular orbit. That means that you not only get power with an electrodynamic tether, but also thrust.

At the Earth, below the geosychronous orbit, the satellite is moving faster around the Earth than the magnetic field, and so you get drag. That is, you lose orbital altitude when you use the electrodynamic tether to draw power.

At Jupiter, the electromagnetic field is going faster above 2.2 Jupiter radii, so that means that you get thrust, in addition to power with the tether.

I would assume that this is the case. This should be looked at, of course. And so, when I show here minus 150 volts per kilometer of conducting tether at the Earth, I'm indicating drag. If you had a low Jupiter orbit, the orbital period is faster than the rotational period, and it's minus 10 kilovolts per kilometer. You switch from 150 volts to 10 kilovolts. If you go up to Io's orbit, the voltage per kilometer is a plus 108 volts per kilometer, which is of the order of low Earth orbit, but positive.

So, the strong Jupiter magnetic field, because you are further away, gives you the equivalent of Earth's magnetic field at Io.

Then, of course, if you go further out, you get lower magnetic field strength, and hence lower voltages per kilometer of tether reducing the power that you could get from the system.

The applications of such a tether at Jupiter are numerous.. Close in to Jupiter, the spacecraft could sample the atmosphere or produce drag. At higher altitudes, the thrust on the tether could aid satellite tours, increase orbital inclination, or rendezvous with a Galilean satellite. In general, the electrodynamic tether would simply help you wherever thrust and power are needed.

The Sun also has a strong magnetic field and a large solar wind. These may be used to draw power, or create drag or thrust as proposed by the Nobel prize winner Hans Alfven. (Figure 12)

Finally, there are other ideas (Figure 13) which I will just throw out here.

1. Anchored lunar satellite proposed by Jerome Pearson in 1979. This is a very long tether off the moon, in order to fling lunar material out towards the L5 point, for example.
2. Use tethers to catch aerobrake vehicles from GEO, Moon and Mars. This would decrease the propellant requirements.
3. Rotating tethers for sensitive gravimetric measurements. Long tethers for sensitive gravity wave detection. The latter was proposed by Bertotti and Thorne.
4. Sample atmospheres of planets using tethers, or scoop the atmosphere for propellant production. Gather up oxygen, for example, with a tethered scooper.
5. Use a ribbon tether for cosmic dust collection, or fly by a comet using a ribbon tether. That is, as you fly by, the comet dust would stick to a deployed ribbon tether, and then be reeled in to be returned back to Earth.
6. Use a tether to capture particles in Saturn's rings. You could orbit Saturn very close to the rings; even above it using low thrust, so that you are in a minor circle instead of a major circle in orbit about Saturn. As the spacecraft orbits above the rings, it can extend a rotating tether, for example, to collect particles in the rings themselves.

Some of these are naturally very futuristic type applications, but we can start thinking about these ideas today.

REFERENCES

Penzo, P.A., "Tethers for Mars Space Operations," AAS Paper 84-174, AAS Science and Technology Series, The Case for Mars II, Vol. 62, 1985

Penzo, P.A., Mayer, H.L., "Tethers and Asteroids for Artificial Gravity Assist in the Solar System," AIAA Paper 84-2056, presented at the AIAA/AAS Astrodynamics Conference, Seattle, Washington, 20-22 August 1984

Uphoff, C.W., Jet Propulsion Laboratory, Pasadena, CA, Internal Memorandum (Mission idea for Figure 1 originated with G. Colombo)

Carroll, J.A., Energy Science Laboratory, San Diego, CA, Private Communication (Figures 2 and 3)

Randolph, J.E., Jet Propulsion Laboratory, (Figure 4 - see NASA Space Systems Technology Model, NASA TM 88174, June 1985).

McCoy, J.E., Johnson Space Center, Clear Lake, TX, Private Communication (Figure 11)

Alfven, H., "Spacecraft Propulsion: New Methods", Science, Vol 176, pp 167-168, 14 April 1972

Pearson, J., "Anchored Lunar Satellites for Cislunar Transportation and Communication", JAS, Vol. 27, No. 1, pp 39-62, Jan. - Mar. 1979

Bright, L.E., "Saturn Ring-Rendezvous Mission Utilizing a Tethered Sub-Satellite", Jet Propulsion Laboratory, Internal Memorandum, 1984

APPLICATIONS OF TETHERS FOR PLANETARY MISSIONS

Applications of Tethers in Space Workshop
Venice, Italy
October 15—17, 1985

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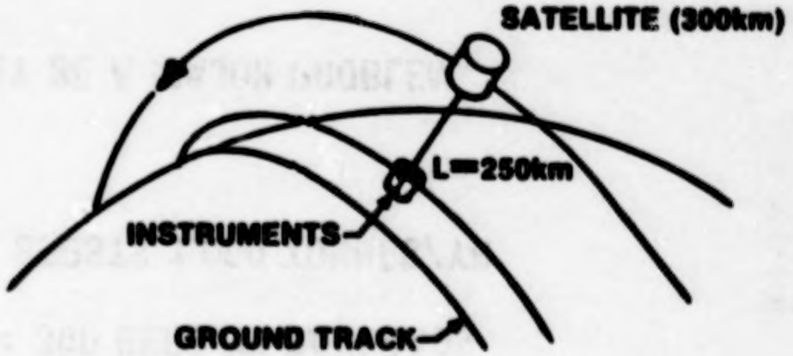
Pasadena, California

Office of Space Flight
Advanced Programs
NASA Headquarters

A TETHERED LUNAR SATELLITE FOR REMOTE SENSING

- CLOSE LUNAR SATELLITES ARE UNSTABLE BECAUSE OF EARTH AND SUN PERTURBATIONS

- AN INSTRUMENT PACKAGE COULD BE TETHERED 50km ABOVE THE SURFACE FROM A SATELLITE IN A STABLE 300km ORBIT


SATELLITE (300km)
L=250km
INSTRUMENTS
GROUND TRACK

- SENSITIVE MEASUREMENTS OF THE MOON'S MAGNETIC FIELD, AND GRAVITATIONAL ANOMALIES COULD THEN BE MADE CLOSE TO THE MOON AND FROM THIS STABLE ORBIT

FIG. 1

LUNAR EQUATOR SURFACE SLING (LESS)

- "MINIMAL MASS-DRIVER" TO LAUNCH 10Kg PAYLOADS INTO LUNAR ORBIT (RELIABLE LOW TECHNOLOGY SYSTEM)
- SYSTEM SHOULD FIT IN 1 SHUTTLE.
- 1000m TETHER AT 16rpm IMPOSES < 300 GEES ON PAYLOADS
- 2 LAUNCHES/10 MIN USES < 100kw, BOOSTS 1,000 TONNES/YR
- TETHER MASS/PAYLOAD RATIO = 4
- COLLISION & DEBRIS GENERATION MAY BE A MAJOR PROBLEM

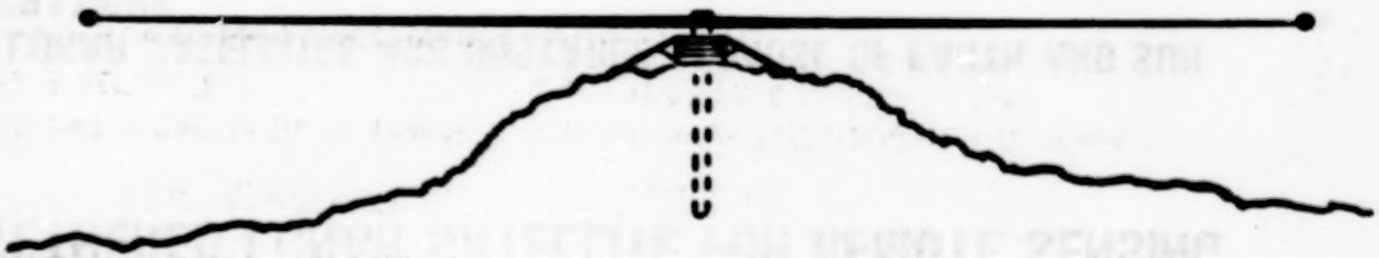


FIG. 2

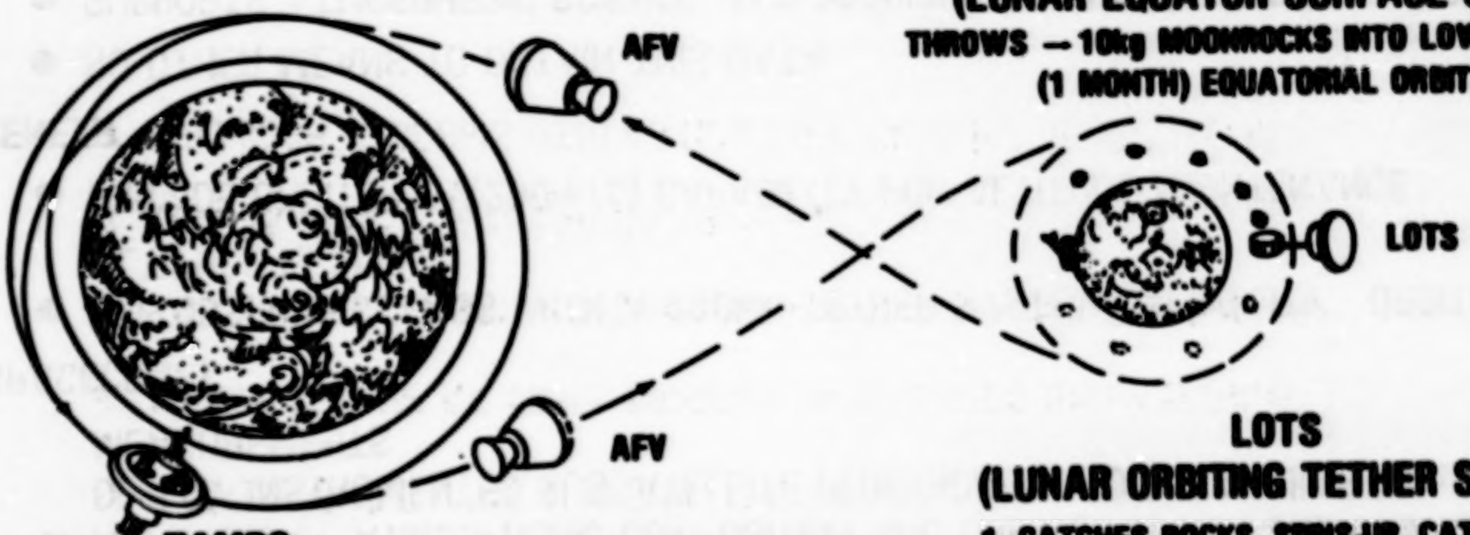
EARTH-MOON TETHER-TRANSPORT INFRASTRUCTURE

AFV (AEROBRAKING FERRY VEHICLE)

1. AEROBRAKES AND IS CAPTURED BY TAMPS
2. IS UNLOADED & REFUELED
3. IS TETHER/ROCKET BOOSTED TO MOON
4. IS CAPTURED & LOADED BY LOTS
5. IS SLUNG BACK TOWARDS EARTH BY LOTS

LESS
(LUNAR EQUATOR SURFACE SLING)

THROWS ~10kg MOONROCKS INTO LOW-LIFETIME (1 MONTH) EQUATORIAL ORBITS



TAMPS
(TETHER AND MATERIALS PROCESSING STATION)

1. CATCHES AEROBRAKED AFV, RETRIEVES & UNLOADS IT
2. PROCESSES MOONROCKS INTO LO$_2$, ETC
3. FUELS AFV & REBOOSTS IT TOWARDS MOON
4. RECOVERS MOMENTUM W/ELECTRODYNAMIC TETHER
5. ALSO CAPTURES, REFUELS, REBOOSTS AFV'S GOING TO GEO & DEEP SPACE

LOTS
(LUNAR ORBITING TETHER STATION)

1. CATCHES ROCKS, SPINS-UP, CATCHES AFV
2. LOADS AFV WITH ½ OF ROCKS
3. SPINS-UP & THROWS AFV TO TEI
4. DESPINS & LOADS OTHER ROCKS ON TETHER
5. SPINS-UP & DEBOOSTS ROCKS FOR MOMENTUM RECOVERY

FIG. 3

MARS AERONOMY ORBITER WITH A TETHERED SATELLITE SYSTEM

PURPOSE

- ANALYSIS OF ATMOSPHERIC COMPOSITION AND CHEMISTRY FOR ONE MARTIAN YEAR. DEPLOY INSTRUMENTED SUBSATELLITE PERIODICALLY TO OBTAIN IN-SITU MEASUREMENTS

SPACECRAFT

- USE OBSERVER CLASS WITH A 200km TETHER SYSTEM CAPABILITY. ORBITER ALTITUDE IS 350km
- PROVIDE ORBITER ΔV(200m/s) CAPABILITY FOR ALTITUDE MAINTENANCE

BENEFIT

- NO OTHER MEANS TO CBTAIN THIS DATA
- SUPPORTS ATMOSPHERIC SCIENCE, AND POSSIBLY MANNED PLANETARY MISSION DEFINITION

OPPORTUNITY

- NASA CURRENTLY PLANS AN OBSERVER MAO FOR LAUNCH IN 1994 OR 1996
- TSS AND OTHER TETHER EXPERIENCE AVAILABLE FOR USE

COST

- TYPICAL OBSERVER COST, $250M + OPERATIONS
- DELTA FOR TETHER SYSTEM AND SUBSATELLITE ESTIMATED AT $100M

FIG. 4

ASTEROID GRAVITY ASSIST FOR MARS MISSIONS

METHOD

- A TETHER IS USED TO ATTACH THE SPACECRAFT TO A NEAR-EARTH ASTEROID TO PRODUCE AN ARTIFICIAL GRAVITY ASSIST TO AID EARTH-MARS TRANSFERS

ADVANTAGES

- ABOUT 50% FUEL SAVINGS POSSIBLE
- LOWER APPROACH VELOCITY AT MARS

SYSTEM

- MANY ATEN ASTEROIDS ONLY 1km DIAMETER WOULD BE CANDIDATES (~2500)
- TETHERS 2—3 x STRONGER THAN KEVLAR DESIRED
- WITH MANY CANDIDATES, PHASING SHOULD BE NO PROBLEM

- NEEDS FURTHER STUDY

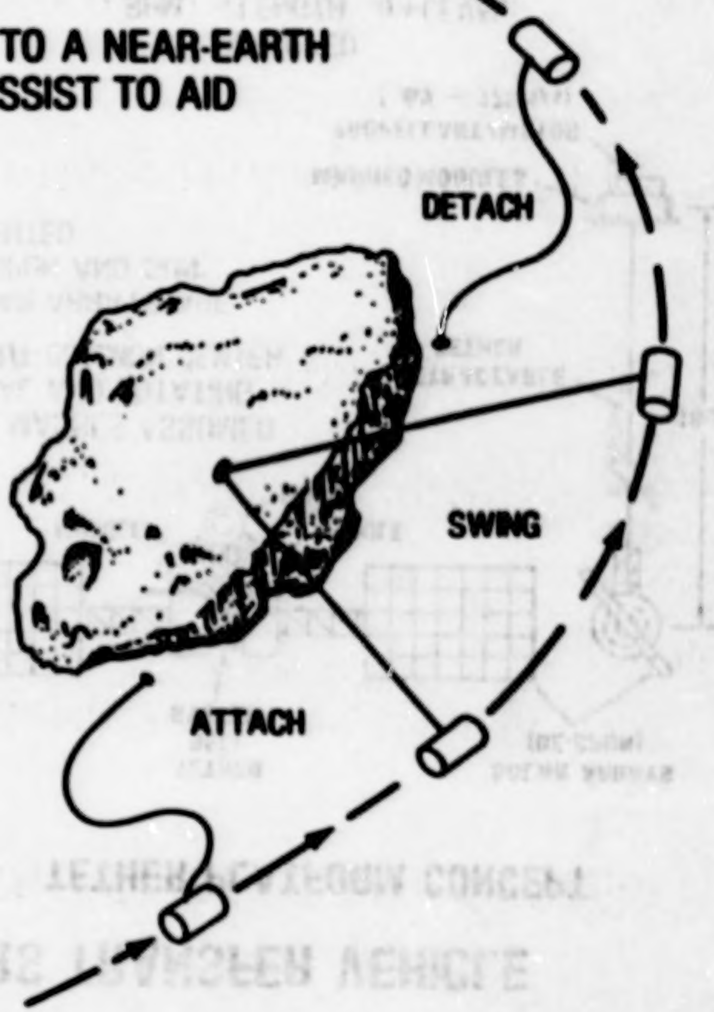
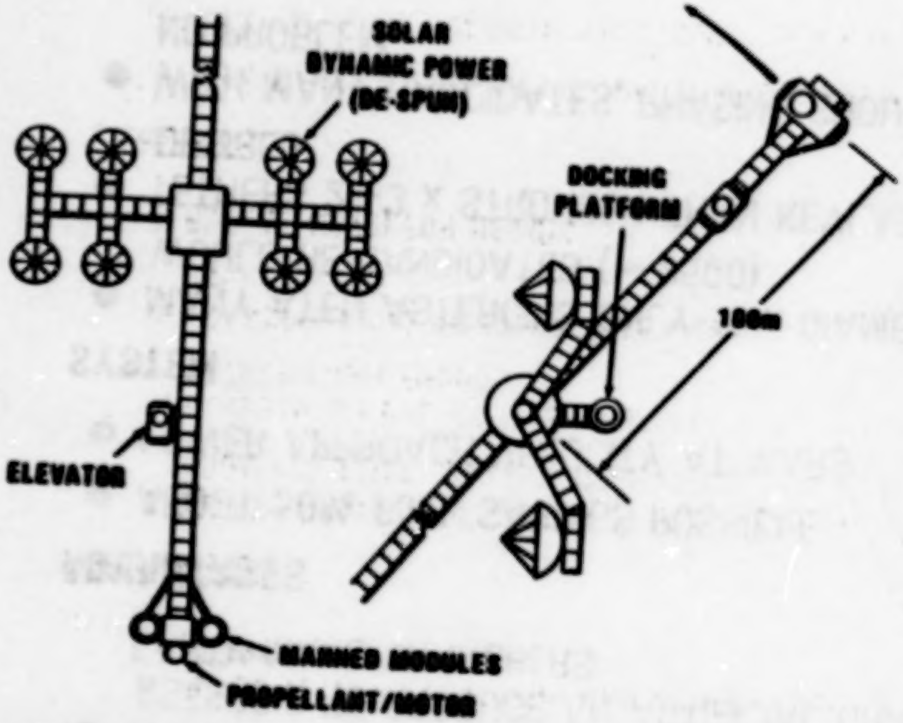


FIG. 5

ARTIFICIAL GRAVITY FOR EARTH—MARS TRANSFER VEHICLE

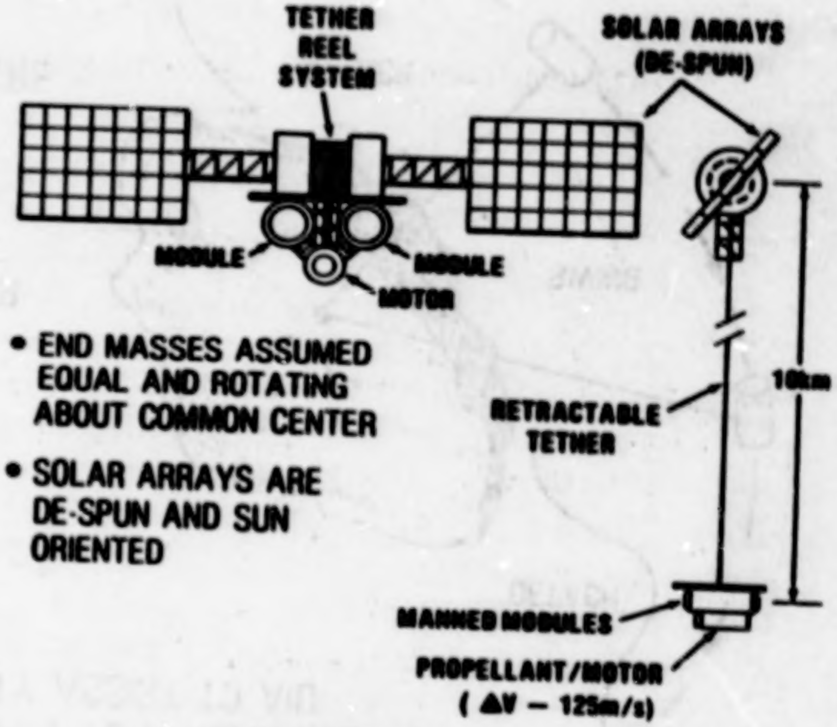
STATION CONCEPT


SOLAR DYNAMIC POWER (DE-SPUN)
DOCKING PLATFORM
100m
ELEVATOR
MANNED MODULES
PROPELLANT/MOTOR

- 4 MODULES, 2 AT EACH END ROTATE ABOUT A COMMON CENTER
- ELEVATOR TRANSFERS MEN, SUPPLIES TO EITHER END

RPM	ΔV	G-LEVEL
1	10m/s	0.11
2	20m/s	0.45
3	30m/s	1.00

TETHER PLATFORM CONCEPT


TETHER REEL SYSTEM
SOLAR ARRAYS (DE-SPUN)
MODULE
MODULE
MOTOR
10km
RETRACTABLE TETHER
MANNED MODULES
PROPELLANT/MOTOR (ΔV – 125m/s)

- END MASSES ASSUMED EQUAL AND ROTATING ABOUT COMMON CENTER
- SOLAR ARRAYS ARE DE-SPUN AND SUN ORIENTED

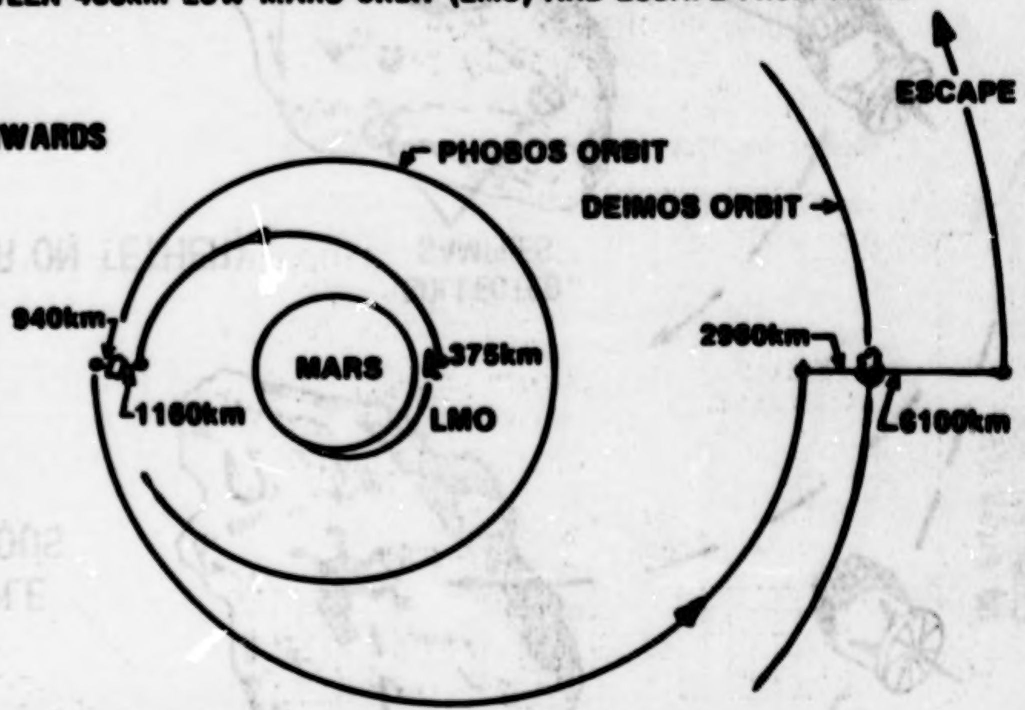
RPM	DEPLOYED LENGTH	g—LEVEL
0.75	4km	1.25
0.48	5km	0.65
0.33	6km	0.38
0.20	8km	0.16
0.12	10km	0.08

Figure 6

MARS SURFACE TO ESCAPE TETHER TRANSPORTATION SYSTEM

OBJECTIVE

- TO TRANSPORT PAYLOADS (P/L) BETWEEN 400km LOW MARS ORBIT (LMO) AND ESCAPE FROM MARS



SYSTEM

- PLACE TETHERS UPWARDS AND DOWNWARDS AT PHOBOS AND DEIMOS

OPERATION

1. TETHER PAYLOAD UPWARDS 375km FROM "SHUTTLE" IN LMO—RELEASE
2. RENDEZVOUS P/L WITH DOWNWARD TETHER FROM PHOBOS
3. TRANSPORT P/L TO UPWARD TETHER AND RELEASE
4. REPEAT (2),(3) FOR DEIMOS

BENEFITS

- THIS SYSTEM USES MOMENTUM OF MARS SATELLITES FOR TRANSFER. SAVES 1.6km/s PROPELLANT
- SYSTEM WORKS IN BOTH DIRECTIONS. CAN HANDLE HEAVY TRAFFIC
- MINIMUM COMPLEXITY SIMPLIFIES SYSTEM MAINTENANCE/REPAIR
- KEVLAR STRENGTH ADEQUATE FOR TETHERS
- TETHER MASS TO P/L RANGES FROM 0.3 TO 5

FIG. 7

COMET/ASTEROID SAMPLE RETURN

CONVENTIONAL APPROACH

- RENDEZVOUS WITH BODY
- RELEASE LANDER, DRILL SAMPLE
- RETURN TO ORBITER, RENDEZVOUS
- RETURN SAMPLES TO EARTH
- COST ESTIMATE, $1.0B

TETHER APPROACH

- RENDEZVOUS WITH BODY
- EJECT PENETRATORS (SAMPLER ON TETHER)
- RETRIEVE SAMPLES
- RETURN SAMPLES TO EARTH
- COST ESTIMATE, $750M

ADVANTAGES

- SAMPLES COLLECTED FROM SEVERAL LOCATIONS
- LOWER COST

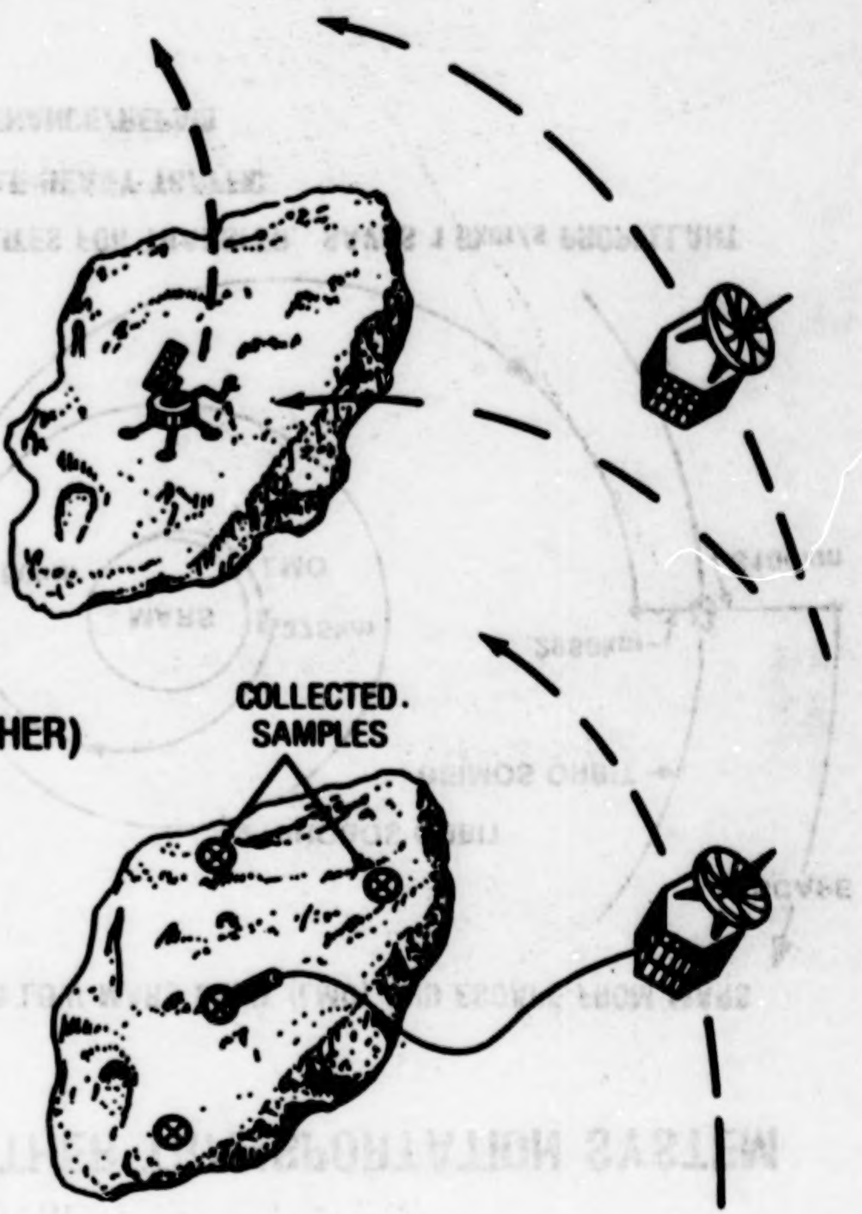
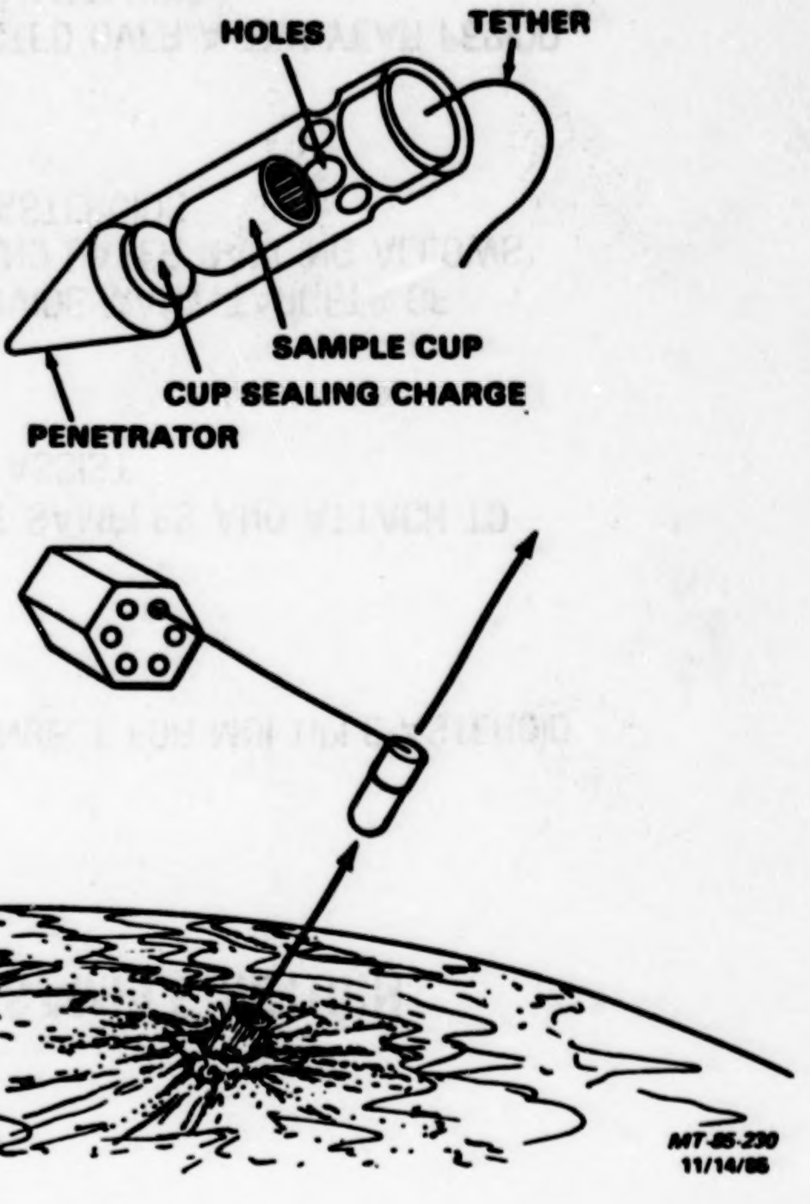


FIG. 8

COMET/ASTEROID SAMPLER SYSTEM

SEQUENCE OF EVENTS

- TETHERED PENETRATOR AT 100m IS SHOT AT TARGET
- ON IMPACT OF PENETRATOR, SAMPLE ENTERS HOLES OF SHELL INTO CUP
- EXPLOSIVE CHARGE SEALS CUP AND EJECTS CUP FROM PENETRATOR SHELL
- VELOCITY CAUSES ROTATION OF TETHER AND TENSION IN TETHER
- S/C THRUSTERS ARE USED TO CONTROL RETRIEVAL OF CUP
- OTHER PENETRATOR/SAMPLERS RETRIEVE SAMPLES FROM OTHER AREAS, OR OTHER BODIES
- S/C WITH SAMPLES RETURN TO EARTH


HOLES
TETHER
SAMPLE CUP
CUP SEALING CHARGE
PENETRATOR

MT-85-230
11/14/85

FIG. 9

MAIN BELT ASTEROID TOUR/SAMPLE RETURN

PURPOSE

- SEND A SPACECRAFT INTO THE MAINBELT FOR MULTIPLE ASTEROID FLYBYS AND SAMPLE COLLECTION

METHOD

- USE A TETHER SYSTEM TO COLLECT SAMPLES AND ATTACH TO ASTEROID FOR ARTIFICIAL GRAVITY ASSIST

ADVANTAGES

- MILLIONS OF SMALL ASTEROIDS PROVIDE MANY TARGETS OF OPPORTUNITY. OPTICAL SENSORS AND LASER RANGING ALLOWS S/C TO MANEUVER FOR FLYBY OF ASTEROIDS

OPERATION

- AFTER MANY SAMPLES ARE COLLECTED OVER A TEN YEAR PERIOD, THEY ARE RETURNED TO EARTH FOR ANALYSIS

FIG. 10

ELECTROMAGNETIC TETHERS AT JUPITER

PHYSICAL PRINCIPLES

- USE THE ELECTRODYNAMIC TETHER IN JUPITER'S STRONG MAGNETIC FIELD FOR THRUST/DRAG
- JUPITER'S RAPID ROTATION PERIOD (10hr) CAUSES THE MAGNETIC FIELD TO MOVE PAST THE GALILEAN SATELLITES. THIS PRODUCES THRUST ON A CONDUCTING TETHER INSTEAD OF DRAG, DRAWING ENERGY FROM JUPITER'S ROTATION.
- INDUCED VOLTAGE:
  - —150v/km (LEO) 108v/km (IO) 21v/km (GANYMEDE)
  - —10kv/km (LJO) 50v/km (EUROPA) 7v/km (CALLISTO)
- DRAG-TO-THRUST CROSSOVER IS ABOUT R=2 JUPITER RADII

APPLICATIONS

- SAMPLE JUPITER'S ATMOSPHERE
- ASSIST GALILEO TYPE SATELLITE TOUR (ALL EQUATORIAL)
- INCREASE ORBIT INCLINATION
- RENDEZVOUS WITH A GALILEAN SATELLITE

BIG QUESTION

- WILL ELECTRODYNAMIC TETHERS WORK BETTER/WORSE THAN AT EARTH?

FIG. 11

HELIOCENTRIC ALFVEN ENGINE

PHYSICAL PRINCIPLE

- ALIGNING A CONDUCTING TETHER WITH THE E FIELD OF THE SOLAR WIND PRODUCES 2V/km. CLOSE CIRCUIT TO PRODUCE POWER (ALFVEN — 1972)

SYSTEM

- USE A 1000km NIOBIUM-TIN SUPERCONDUCTING WIRE TO PRODUCE 1000amps (2MW)
- PLACE IN ALUMINUM TUBE WITH FLOW OF SUPERCOOLED (2°k) HELIUM
- INSULATE TUBE AND PLACE REFRIGERATION SYSTEMS AT EACH END
- MAKE ELECTRICAL CONTACT AT ENDS WITH SOLAR WIND

APPLICATIONS

- USE DRAG ON WIRE TO SPIRAL INTO (OR OUT FROM) SUN, OR TO MOVE OUT OF ECLIPTIC
- USE POWER TO DRIVE ION ENGINE

QUESTIONS

- WHAT ARE COMPETITIVE SYSTEMS? SOLAR SAIL? NUCLEAR?
- FEASIBILITY NOT ESTABLISHED
- CONTROLLABILITY NOT ESTABLISHED

FIG. 12

ADDITIONAL IDEAS FOR PLANETARY MISSIONS

- ANCHORED LUNAR SATELLITES (J. Pearson, 1979)
- USE TETHER TO CATCH AEROBRAKED VEHICLES FROM GEO, MOON, MARS
- ROTATING TETHERS FOR SENSITIVE GRAVITY MEASUREMENTS
- LONG TETHERS FOR SENSITIVE GRAVITY WAVE DETECTION (B. Bertotti , K. Thorne)
- SAMPLE ATMOSPHERES OF PLANETS/SATELLITES FOR ANALYSIS OR PROPELLANT PRODUCTION
- USE RIBBON TETHER FOR COSMIC DUST COLLECTION
- USE TETHER TO CAPTURE PARTICLES IN SATURN'S RINGS

FIG. 13

N86-28414

ELECTRODYNAMIC INTERACTIONS

Marino Dobrowolny
Istituto Fisica Spazio Interplanetario CNR

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I will give a general introduction on the electrodynamic interaction of long metallic tethers with the ionosphere. Although I will not get into any detail, this will serve as a basis for J. McCoy's presentation on the use of electrodynamic tethers for power generation and thrust.

Figure 1 shows the basic concept of electrodynamic tethers. It refers explicitly the TSS but, of course, the concept is more general. Due to the tether's motion across the Earth's field, we have a polarization electric field along the tether. For an observer at rest in the ionosphere, this is given by

$$\underline{E} = -\underline{V} \times \underline{B}$$

and is so directed that the upper end of the system is positive with respect to the lower end. For this reason, in a system like TSS where the tether is coated with dielectric and the electrical contact is between its two terminations and the ionosphere, the upper end termination will collect electrons and, in a passive system, the lower end will collect ions. Alternatively, with a plasma emitter or electron gun at the lower end, the electrons collected above will be re-emitted in the ionosphere.

For the tether of TSS 1, the voltage across the tether amounts to a maximum value

$$V_{max} \sim 5K \text{ volts}$$

and, of course, varies along the orbit. In general, space charge regions will develop around the two terminations of the system, which can be at considerable potential with respect to the unperturbed ionospheric plasma and the current in the tether will be most significantly determined by local processes in such space charge regions.

Our knowledge of the behavior of highly charged bodies in a following plasma in a magnetic field is indeed quite limited, both theoretically and from the laboratory point of view, and the investigation of such local processes is certainly the primary goal of the first TSS electrodynamic mission.

Having pointed out the importance of these local processes, let me now outline a qualitative view of the global perturbation induced by TSS in the ionosphere (see Figure 2). An observer sitting on the tether will see a dc current in the tether itself going out into the ionosphere along the magnetic flux tubes intercepted by its two terminations. The current, as indicated in the figure, is assumed to go away along such magnetic flux tubes until it reaches an altitude low enough that conductivity transverse to magnetic field lines becomes appreciable and allows current closure across the ionosphere.

The picture is different for an observer in the ionosphere or on the Earth's surface. At a certain time the tether will apply a voltage between the flux tubes intercepted by its two terminations at that time. The voltage pulse will last a time

$$T \sim \frac{D}{V}$$

where V is the system velocity and D is one dimension transverse to the motion. As the charge separation set up by the tether, at that given time cannot be discharged across magnetic field lines, it will rather be propagated as a pulse in the ionosphere. The duration of the pulse also sets up the upper limiting frequency

$$f^* \sim \frac{1}{T}$$

of the electromagnetic radiation caused by the tether's motion. If we use for D the diameter of the TSS satellite ($D = 1.2$m) we obtain $f^* \sim 7$ kHz so that the perturbation will include not only low frequency EM waves but will extend in the whistler range. One of the interesting applications of electrodynamic tethers, as you all know, is that of using them as low frequency wave generators to communicate to the Earth at ELF/ULF. There are theoretical investigations of the power emitted by long tethers at these low frequencies which give the indication of low powers in the ionosphere (typically 1 watt for 1 ampere and 100 km tether). Such investigations are, however, based on very simplified models, and the truth is that we have not been able so far to adequately describe the phenomenon. Ground observations of TSS radiation are indeed foreseen in conjunction with the first TSS flight, and perhaps will give some positive indication of the phenomenon. For the understanding of the global perturbation associated with electrodynamic tethers, it would, however, be essential to have ionospheric measurements from a free flyer at variable distances from the tether system and on magnetic flux tubes intercepted by the tether.

Based on what I have said about local interaction processes and the global interaction with the ionosphere, let me now describe an equivalent circuit of the tether system (see Figure 3). Here Z_E represents the impedance of the current closure in the ionospheric E layer. Z_{TR} represents the impedance of the magnetic flux tubes intercepted by the two terminations of the system which act as transmission lines in the ionosphere. Z_{ORB} and Z_{SAT} represent the impedances of the space charge regions around the orbit and the satellite, for the case of TSS, or in any case, around the two conducting terminations of any tether system. In terms of what I have said before, Z_{TR} represents the effect of the tether's radiation or, if you like, the global perturbation induced by the moving tether in the ionosphere. On the other hand, Z_{ORB} and Z_{SAT} represent the local interaction processes determining charged particle collection.

In this same figure I have also written the basic equation of the circuit. What is written is, more precisely, that the total voltage drop across the tether ($\Delta V = VBL - RI$) which is given by the electromotive force due to the motion minus the ohmic losses due to the tether's internal resistance, equals the sum of all the remaining potential drops in the circuit

$$\Delta V = VBL - RI = \Delta\phi_{ORB} + \Delta\phi_{SAT} + \Delta\phi_{I}$$

Of these, $\Delta\phi_I$ is the total potential drop across the ionosphere and hence represents the magnitude of the pulse which is really applied to the ionosphere. On the other hand, $\Delta\phi_{ORB}$ and $\Delta\phi_{SAT}$ represent the potential drops across the space charge regions around the two terminations of the system. The problem with this equation is that $\Delta\phi_{ORB}$ and $\Delta\phi_{SAT}$ are complex nonlinear and unknown functions of the current in the tether.

These are the results of the local interactions that I was talking about before. We also see clearly from this equation that global and local interactions are part of the same picture and, for example, until the current voltage characteristics are determined, we cannot tell how much of the perturbation is applied to the ionosphere. It is also clear from the same equation that, in order to have maximum current in the tether, we have to reduce as much as possible $\Delta\phi_{ORB}$ and $\Delta\phi_{SAT}$, i.e., improve the electrical contact between the two terminations of the system and the ionosphere. This is indeed the situation one should aim at for the purpose of such applications as power generation and thrust.

BASIC CONCEPT OF ELECTRODYNAMIC TETHER

$\underline{E} = -\underline{V} \times \underline{B}$

$\Delta\Phi_{MAX} \sim 5\,\mathrm{Kv}$ (TSS1)

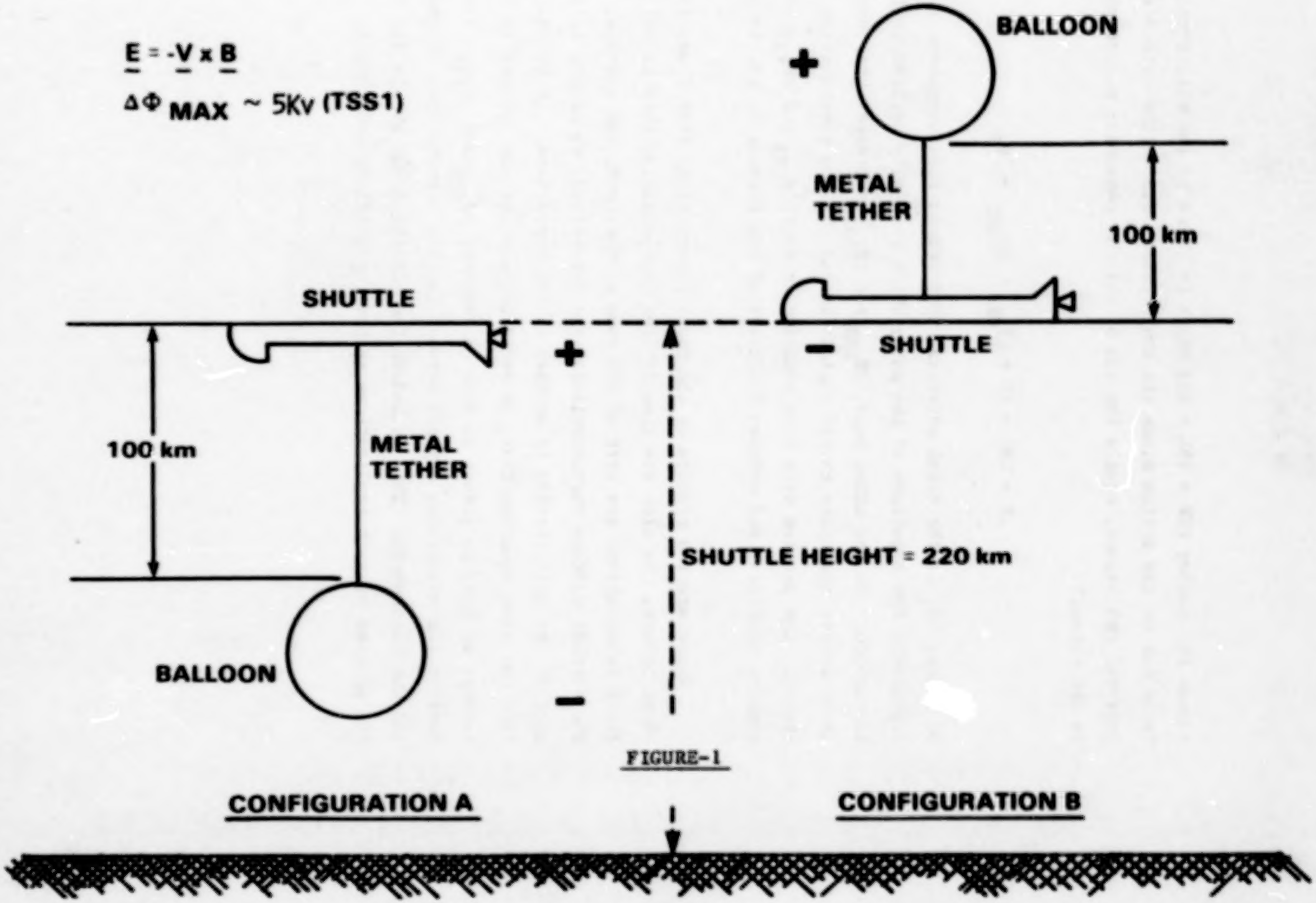
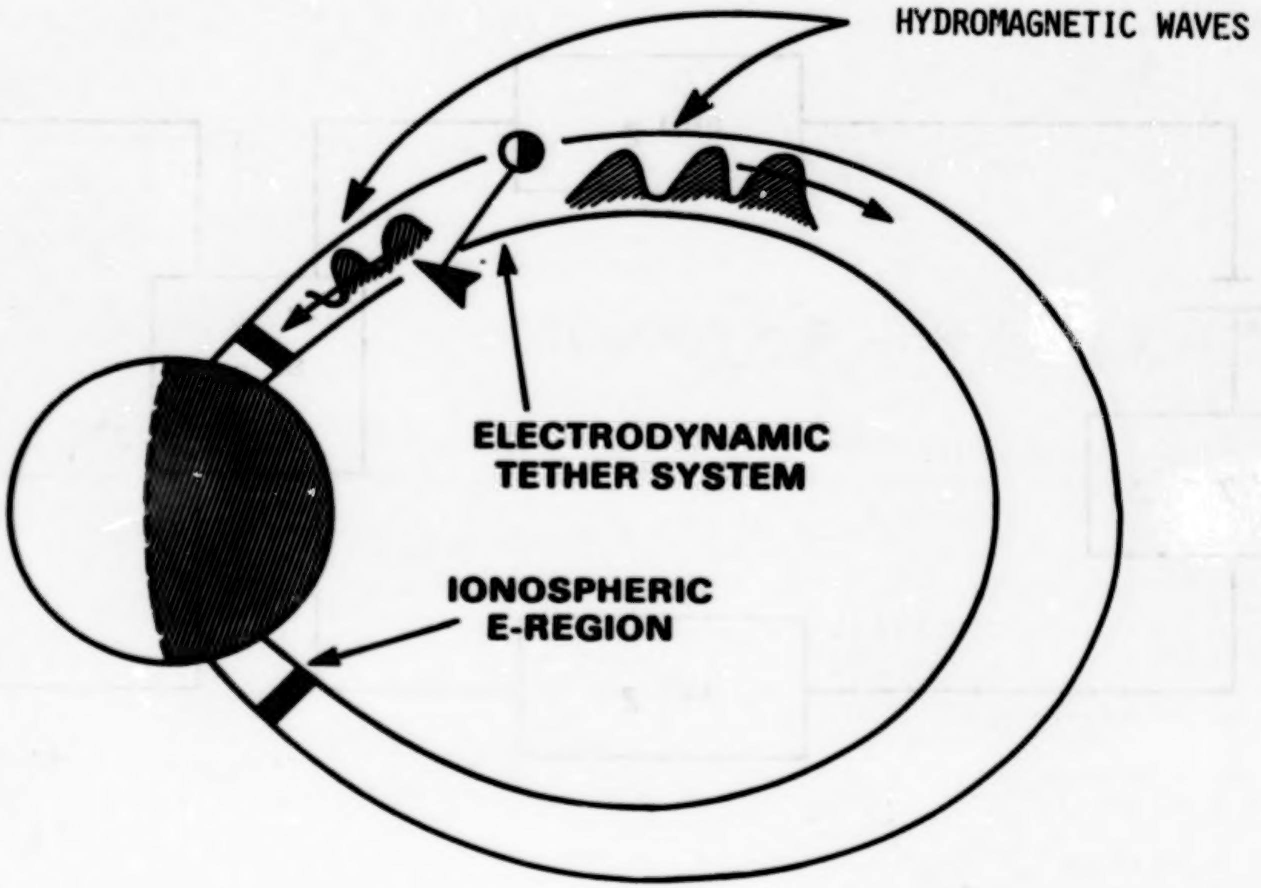

BALLOON
+
METAL
TETHER
100 km
SHUTTLE
–
SHUTTLE
+
100 km
METAL
TETHER
SHUTTLE HEIGHT = 220 km
BALLOON
–
CONFIGURATION A
CONFIGURATION B

FIGURE-1

GLOBAL IONOSPHERIC PERTURBATION INDUCED BY ELECTRODYNAMIC TETHER

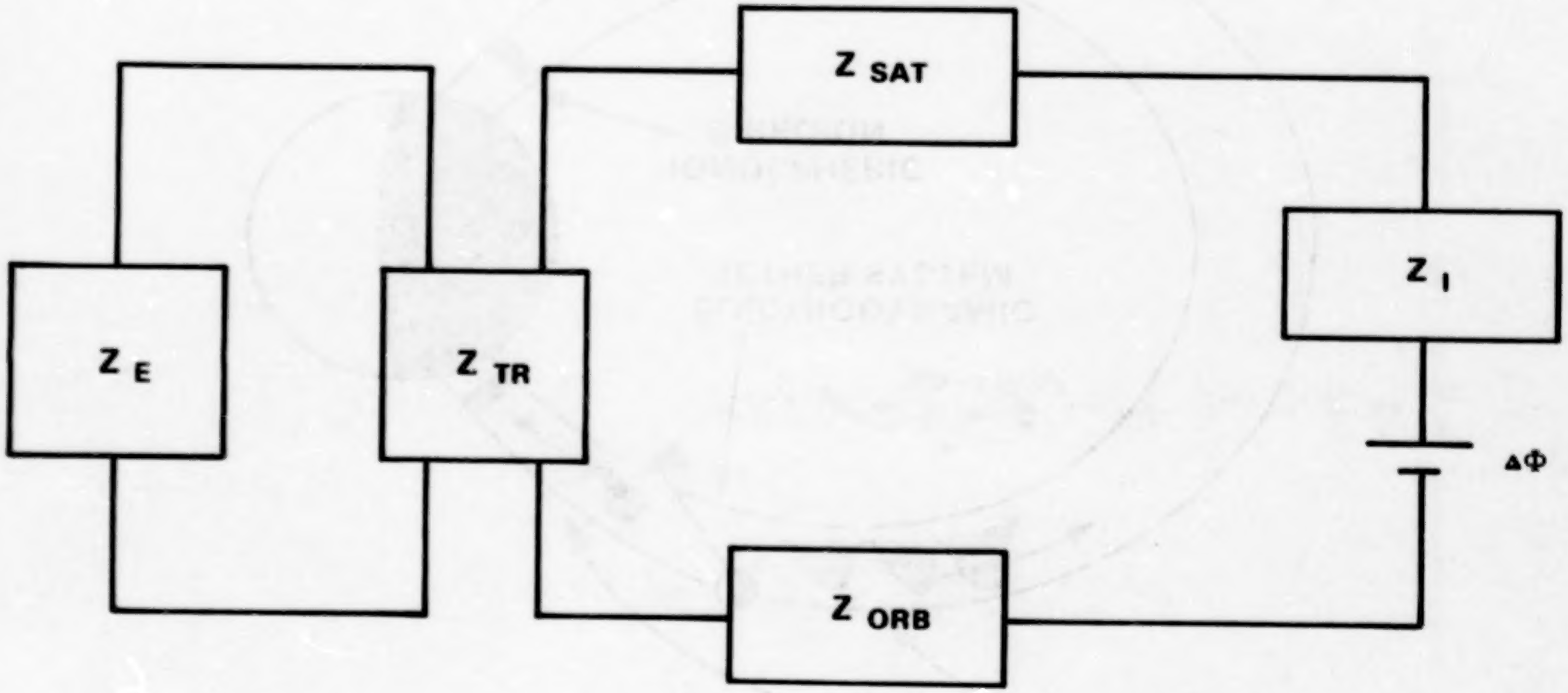

HYDROMAGNETIC WAVES
ELECTRODYNAMIC TETHER SYSTEM
IONOSPHERIC E-REGION

$T \sim \frac{D}{V}$

$f < f^{*} \sim \frac{1}{T}$

FIGURE-2

CIRCUIT EQUIVALENT OF ELECTRODYNAMIC TETHER


Z_E
Z_{TR}
Z_{SAT}
Z_{ORB}
Z_I
$\Delta\Phi$

$$\Delta\Phi \equiv \mathrm{VBL\text{-}RI} = \Delta\Phi_I + \Delta\Phi\,\mathrm{ORB} + \Delta\Phi\,\mathrm{SAT}$$

FIGURE-3

N86-28415

ELECTRODYNAMIC INTERACTIONS

James McCoy
Johnson Space Center, NASA

To begin with, I will be concentrating mostly on power and thrust applications, although there are a number of other applications of the electrodynamic tether.

To orient you, (Fig. 1) these two very similar looking spacecraft configurations are exact opposites. This is a power generator, and this is a motor.

The differences are just a little bit subtle. The induced voltage in the tether wire is in the same direction in both cases, and the difference involves whether you allow that voltage to drive a current to generate power.

Or, if you use an onboard power supply with a higher voltage to drive a current in the opposite direction, which then provides thrust.

If you are generating power, the magnetic field's (IXB) force on the current in the tether wire is directed against the orbital velocity and gives you a drag force. Neglecting losses in the system, this force provides exactly the mechanical work (F·V, in joules/sec) to balance the amount of power that you are producing (in watts) as electricity.

The forces and currents in the motor operation are in the opposite direction, but the forces and the flow of energy still balance, neglecting electrical resistance losses, air drag and so forth. The electrical power that is involved in driving this current against the induced voltage in the tether is exactly equal to the mechanical energy being added into the orbit by accelerating the spacecraft.

The key factor in doing this is the fact that you have a return circuit, which is stationary throughout, for the current due to the moving "armature wire", if you will. in this "motor-generator" system.

ELECTRODYNAMIC TETHER PRINCIPLES

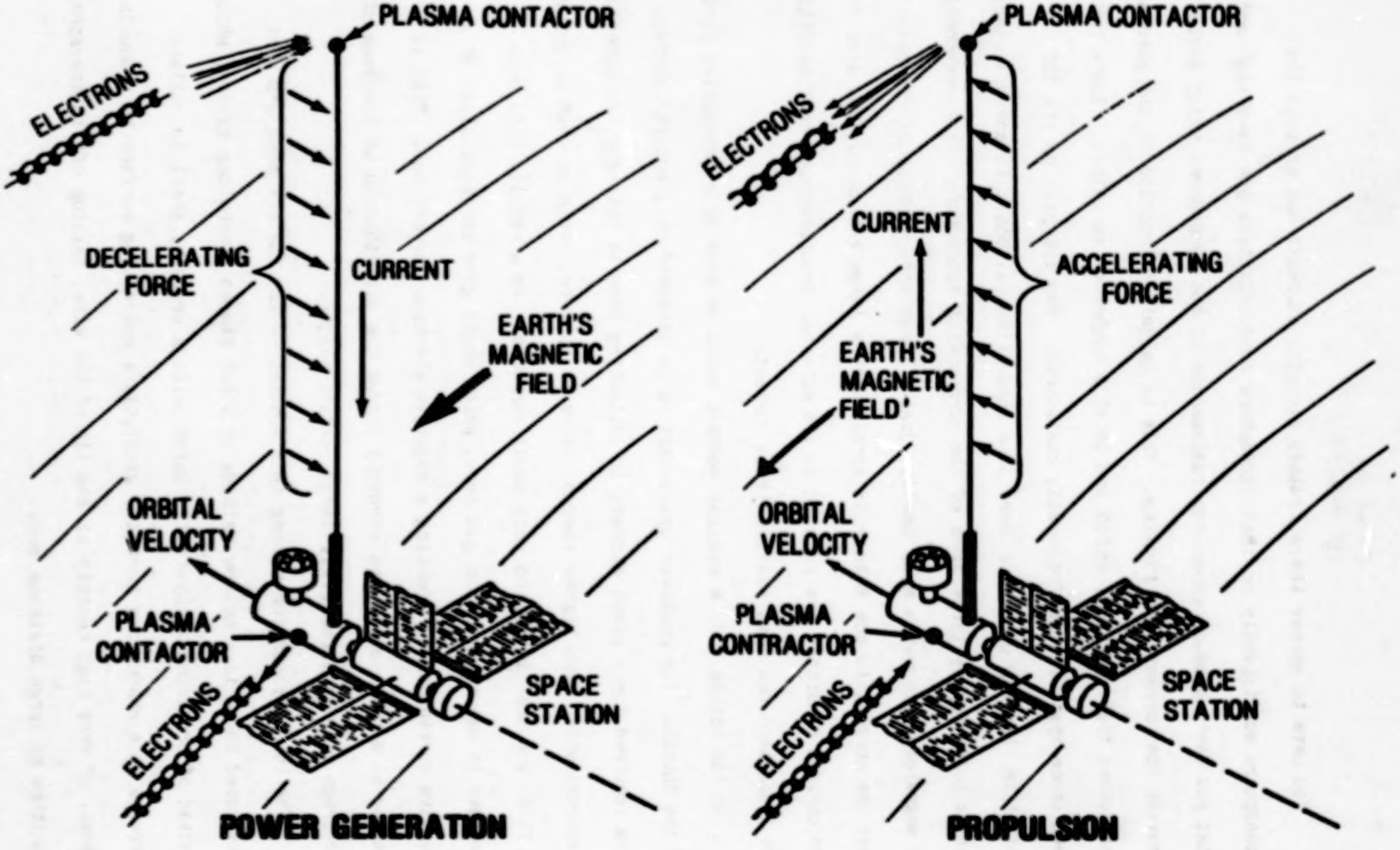

PLASMA CONTACTOR
ELECTRONS
DECELERATING FORCE
CURRENT
EARTH'S MAGNETIC FIELD
ORBITAL VELOCITY
PLASMA CONTACTOR
ELECTRONS
SPACE STATION
POWER GENERATION
PLASMA CONTACTOR
ELECTRONS
CURRENT
ACCELERATING FORCE
EARTH'S MAGNETIC FIELD'
ORBITAL VELOCITY
PLASMA CONTRACTOR
ELECTRONS
SPACE STATION
PROPULSION

Figure 1

You have to spread these (return circuit) currents out through the ionosphere sufficiently so that ionosphere conductivities are very high and so that you don't produce anomalous resistances in the ionosphere which would prevent the current from flowing. This is largely a function of the plasma contactors that are used, which can be of a number of varieties. There have been three systems most frequently considered. For example, on the TSS satellite, the top contactor here is a conducting balloon. It makes contact over a sufficiently large area of the surrounding ionosphere via a combination of magnetodynamic waves and, mostly, just a large enough physical dimension so that the current in the tether is spread over a large enough surface area that the current densities are reduced to the external ionosphere current densities. The ionosphere can then sustain these currents.

At the bottom end, a similar contact could be made by a conductive surface of the Shuttle (or whatever spacecraft it is attached to), but the surface area required for a given current in collecting ions at this end, as opposed to electrons which have higher thermal currents up here, would be much larger and, in fact, you are limited to very small currents. As a result, it's been proposed to use an electron gun here, which would give the equivalent of a positive current in by ejecting a negative electron current out. This is ejected at a high energy and strongly forces the distribution of the beam of electrons over an effectively large contact region.

The third system for making this contact -- and the one that I'm most interested in -- is a hollow cathode or other plasma generating system, which, instead of producing a physically large balloon or metal shell to collect currents on a conducting surface, generates a conducting surface by producing a plasma, of very high density at the tip of the wire, falling off to ionospheric densities at large distance away.

The thermal currents anywhere within this "plasma ball", if you will, are able to -- should be able to -- conduct the tether currents through the system and provide you with good conductive contact if you are able to maintain this "plasma ball" with a sufficient dimension and you are able to maintain high conductivity through the ball without it being impeded (by magnetic fields or plasma instabilities for example).

Those are the three concepts that have generally been used and that we have been studying the last few years for applications.

This (fig 2) is a summary from about a year ago that really presents, I think, about the state we're in right now.

The findings of interest were our conclusions that, for the primary power and thrust applications, the hollow cathode seems to be far superior to the electron gun for producing high current contact to the ionosphere. This is by no means unchallenged, and it is by no means completely exclusive -- for particular applications, other methods, such as passive collection or electron guns for a particular application, may be desirable.

This led to a study of something that I refer to as the Plasma Motor Generator (PMG) because, as well as being capable of much higher currents, it's capable of being reversible. You can reverse the currents without having to swap ends with the balloon and the electron gun or duplicate them at the two ends. And nobody has to turn a switch to change from one to the other.

These systems, basically, appear favorable for very high efficiency operation at a kilowatt to a megawatt of power and involve much shorter and more massive conducting tethers than the low current systems. Ten to twenty kilometers of aluminum conductor weighing perhaps a thousand to a few thousand kilograms would be used for the tether wire.

The dynamics of these things are also rather different from the light

ELECTRODYNAMIC TETHER

FY84 FINDINGS

⊙ ENGINEERING STUDY OF TETHER POWER GENERATOR

⊙ HOLLOW CATHODE FAR SUPERIOR TO ELECTRON GUN FOR CURRENT CONTACT

* STUDY AND PRELIM DESIGN OF PLASMA MOTOR/GENERATOR SYSTEMS
>90% EFFICIENCY for OPERATION AT 1 KILOWATT - 1 MEGAWATT
  * 20KW REF SYSTEM: 10 KM #2-AWG ALUMINIUM/TEFLON 1200 KG
  * 200KW/25 NEWTON REF SYSTEM: 20 KM #00 AL/TEFLON 4100 KG

⊙ STUDY OF MASSIVE TETHER DYNAMICS: IXB @20-200KW, NO SATELLITE

* GENERATOR REQUIRES VARIABLE DC LOAD IMPEDANCE TO CONTROL I (KW)

* MOTOR REQUIRES VARIABLE POWER SUPPLY VOLTAGE TO CONTROL I (N)

* PRELIMINARY SHUTTLE/TETHER CHARGING MODEL

* FEASIBILITY STUDY OF TETHER/RESISTOJET 2KW/ASTRONAUT CONCEPT

* ELECTRICAL COMPONENTS NEED TECHNOLOGY FOR 1-4KV (2KV MIN.)

⊙ MOST PROMISING APPLICATIONS IDENTIFIED:
  * USE WITH SOLAR ARRAY TO OFFSET DRAG IN LEO
  * USE WITH SOLAR ARRAY TO REPLACE BATTERY POWER STOREAGE
  * USE FOR ORBITAL MANUEVERING PROPULSION
  * USE WITH FREE-FLYER FOR STATIONKEEPING, THRUST, & POWER

⊙ PRELIMINARY DESIGN OF PMG/HOLLOW CATHODE VERIFICATION TEST

Figure 2

tether with a massive satellite at the end. These would have no appreciable satellite on the end at all. The mass of the system providing the stabilizing tension in the tether is entirely in the cable itself, and the deflection forces are dominantly the I Cross B (IXB) force terms. Most of the concepts would involve these systems being permanently anchored to a spacecraft which, of necessity, then would be permanently in orbit, rather than something that you reel out and reel back in for a couple of days operation.

Again, there would be specialized applications using either a disposable tether or perhaps one with a reeling system at the far end of the massive cable to provide additional stability.

The concepts that have appeared most promising to us and are receiving the strongest study right now are using PMG's with solar arrays to provide power to the tether. These are intended mostly to generate thrust, rather than to produce power. These concepts are: A system to offset drag in low earth orbit; To replace batteries to store power during the daytime and then take it back out of the orbit at night, with any solar array based power system; For general orbital maneuvering propulsion, using electrical power only. When used in the thrsut mode, the tether provides continuous low thrust levels, without requiring large amounts of mass expended over a long period of time.

Examples of farther-out uses include station keeping for orbital platforms, thrust and power in a combination package, or extremely high delta-V spacecraft for use in orbit around Jupiter or Saturn.

The reason why we've come to favor the hollow cathodes for the current conduction applications is illustrated here (fig. 3).

In terms of the amount of power that can be extracted and the amount of the available electrical energy that is used in the process of carrying these currents to the ionosphere, today's electron guns typically require something

PMG - 20 KW REFERENCE SYSTEM

TETHER LENGTH	10 KM	WORKING TENSION	21 N
NOMINAL VOLTAGE	2 KV	WORKING ANGLE	7 DEG
RATED POWER	20 KW	RATED THRUST	2.5 N
PEAK POWER	125 KW	PEAK THRUST	>40. N

CONDUCTOR	#2 AWG ALUMINUM WIRE DIAMETER 6.5 MM @ 20°C RESISTANCE 8.4 OHMS @ 20°C 7.7 OHMS @ 0°C 7.1 OHMS @-20°C	908 KG
INSULATION	0.5 MM TEFLON (100 VOLTS/MIL)	99 KG
FAR END MASS	10 AMP HOLLOW CATHODE ASS'Y (INCLUDING ELECTRONICS & CONTROL)	10 KG
TETHER CONTROLLER	ELECTRONICS & MISC. HDWR. (POWER DISSIPATION LOSSES @1% = 200W)	83 KG
ARGON SUPPLY & CONTINGENCY RESERVE		100 KG
TOTAL		1,200 KG

TETHER DYNAMICS CONTROL	PASSIVE, IXB PHASING
TETHER CURRENT/POWER CONTROL	DC IMPEDANCE MATCHING
TETHER OUTSIDE DIAMETER	7.5 MM
TETHER BALLISTIC DRAG AREA	75 SQ. METERS

DRAG FORCE @ 10^{-11} KG/M^3 (300 KM 1976 USSA-400 KM SOLAR MAX)	.045 N	.36 KW
I^2R LOSSES @ 20 KW		.77 KW
HOLLOW CATHODE POWER		.50 KW
IONOSPHERIC LOSS @ 10 AMP		.05 KW
TOTAL PRIMARY LOSSES		1.68 KW
EFFICIENCY	ELECTRIC (18.68 KW NET @ 10 AMP/20 KW) OVERALL (20.36 MECH. TO 18.68 ELEC. KW)	93.4% 91.7%
INCLUDING CONTROLLER/POWER PROCESSER LOSSES @ 1%		.20 KW
TOTAL (NET POWER OUT 18.48 KW)		1.88 KW
FINAL EFFICIENCY	ELECTRIC = 92.4%	OVERALL = 90.8%

Figure 3

like a kilovolt of acceleration voltage for an ampere of current, which consumes a lot of the available power, and also produces a substantial heat problem.

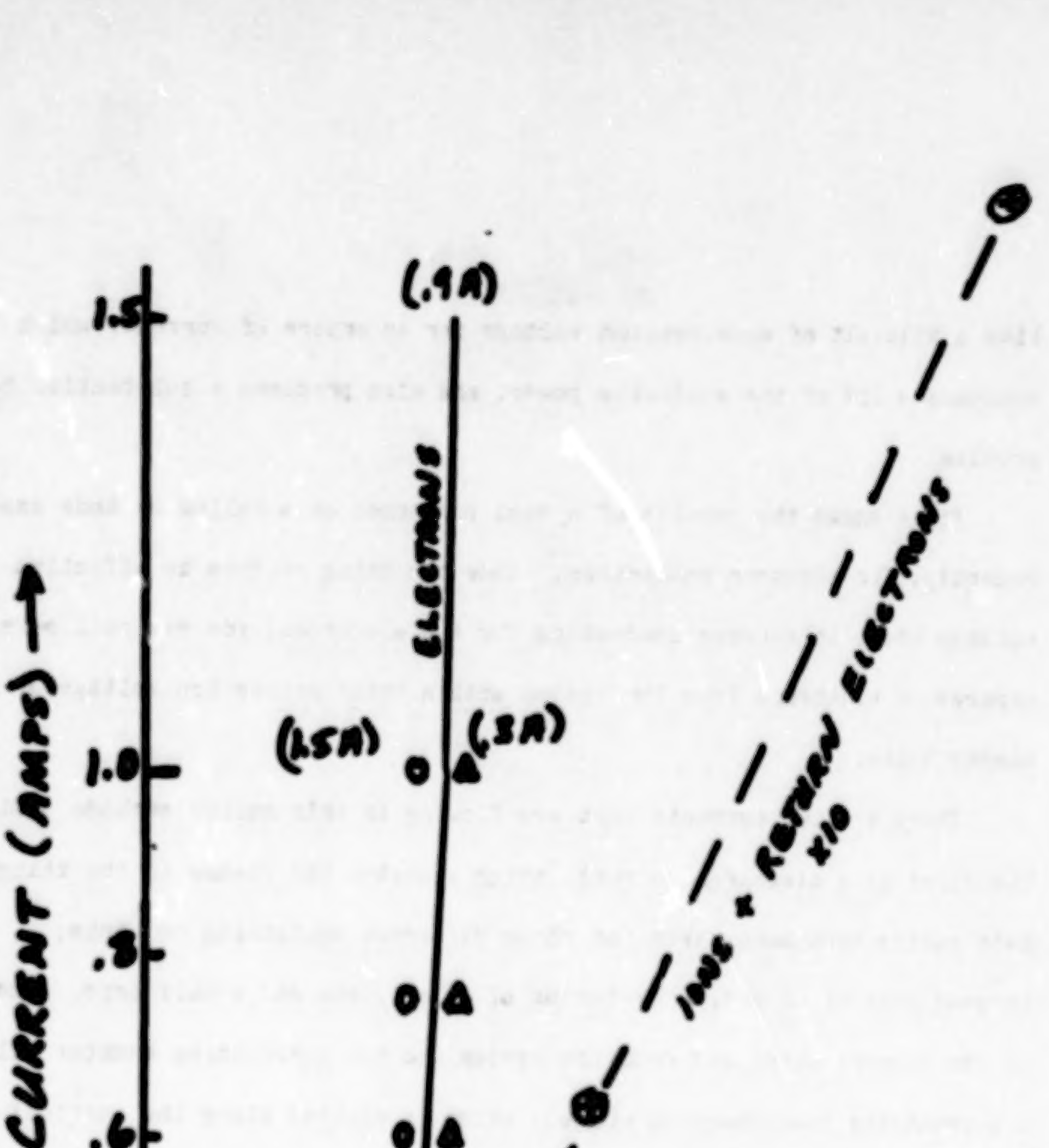
Fig 4 shows the results of a test performed on a hollow cathode assembly recently, for electron extraction. Once the thing reaches an effective turn-on voltage where it becomes conducting for the electrons, you can pull several amperes of electrons from the system with a total extraction voltage of ten or twenty volts.

There are two currents that are flowing in this hollow cathode system. The first is a discharge current. which sustains the plasma in the thing, the data points here were taken for three different sustaining currents; three-tenths of an amp, nine-tenths of an amp, one and a half amps. The second is the current extracted from the system (to the surrounding chamber walls, or a surrounding ionosphere in space), which is plotted along the vertical axis versus extraction voltage on the horizontal scale.

You will notice that. even for extracted currents of an amp or more. well in excess of the basic sustaining current, there is little dependence on sustaining current. The tether current capacity is well in excess of the hollow cathode discharge current, the one you have to expend power to drive with internal power supplies to keep the thing operating. Even the 0.3 amp discharge (less than 10 watts) can easily carry tether currents in excess of an ampere.

There is another characteristic of the hollow cathode system which is perhaps even more attractive. And that is that the tether current can be reversed. You can also use it to draw a positive current.

The positive current drawn from this device is shown as this curve here(labeled "ions"), and this is times ten. It's magnified ten times. It's



SN004 HCA — 18 SCCM XENON
VARIOUS ANODE CURRENTS

Figure 4

actually a rather small current, relatively speaking. But it allows the tether current to be reversed. And, more importantly, this current is not the one that directly provides the current from a tether to the ionosphere. It simply provides the plasma required to maintain conductive conditions. If you turn on an external source of electrons, then, instead of drawing ions from the cathode, it provides a very conductive path for those electrons to reach the cathode, (which was this data here). The thing is able to conduct an electron current that is many times the ion current produced from within its discharge.

The result is that you can design tether systems to operate at higher currents, which get the same power at much lower voltages. This can allow you to either use a shorter tether and operate at operating voltages of one to a few kilovolts, which are more reasonable to engineer power processing systems for, or can allow you to go to extremely high powers.

For tether power generation, as illustrated here (fig 5), we studied net power delivered to a load by a tether length of 20 kilometers, which would give a nominal working voltage of four kilovolts. The curves show net electrical power produced by tethers of three different masses. Heavier cables have lower resistance, allowing higher powers and/or higher efficiency of power production.

To make up this mechanical power (converted to electrical), either you can expend a propellant in a rocket system; which is more efficient for an intermediate term of operations than, for example, fuel cells in terms of kilowatt hours of electricity produced per kilogram of consumables.

Or you can use excess fuel from some other operation.

Or you can kill off excess orbital altitude that you want to get rid of for some reason.

In later applications, this altitude might very well come from some of the

TETHER POWER GENERATOR

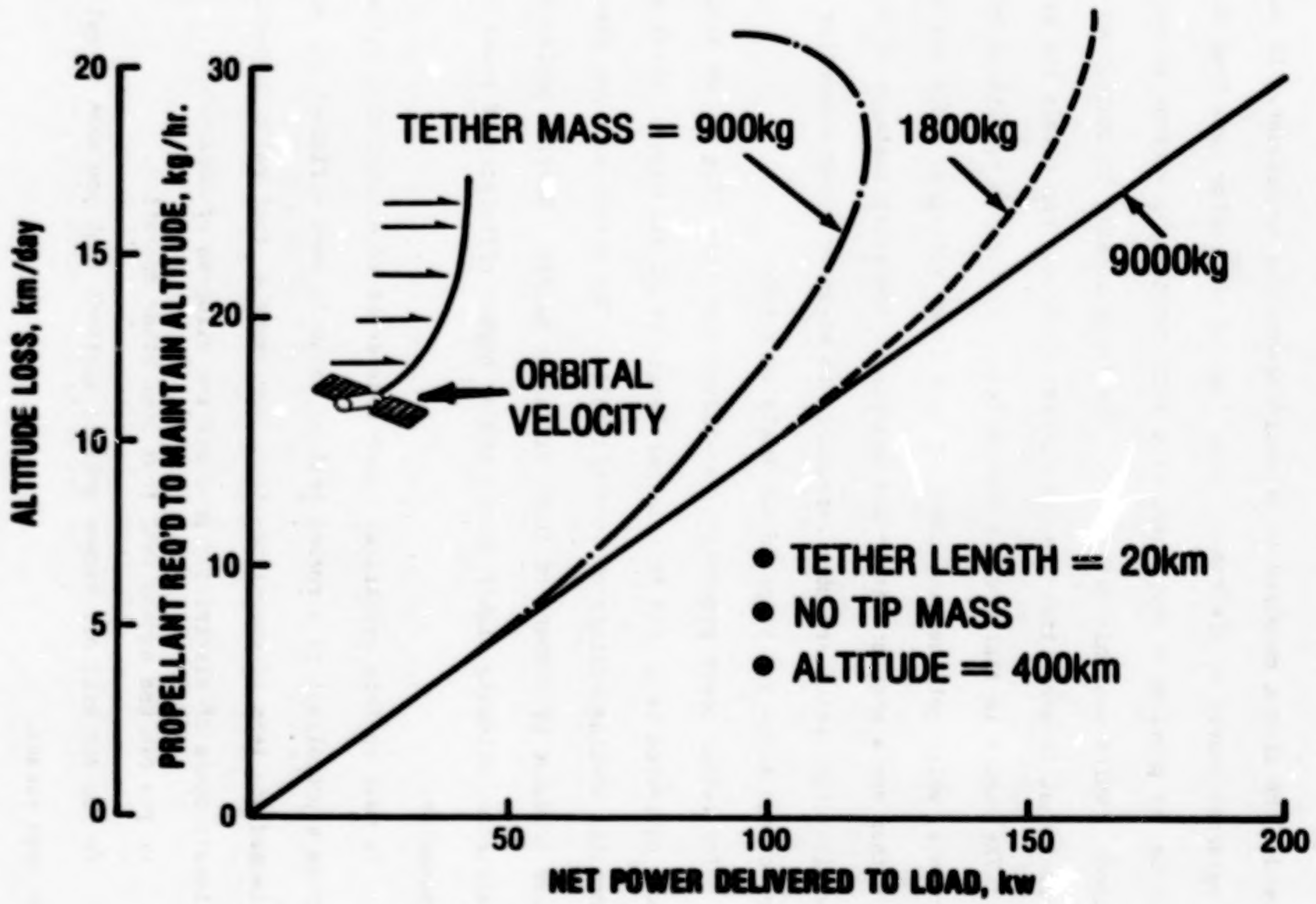


Figure 5

tether transportation concepts where the de-orbiting of the Shuttle is done via a non-conducting tether, which results in boosting the spacestation or whatever to a higher orbit, and you could then utilize that orbital energy (beyond what was needed for drag makeup, among other things) to produce power.

As I mentioned, the concept that I have been finding more interesting is using the thing as a propulsion system. (fig 6) Again, a similar type system at energies of tens of kilowatts would produce Newtons of thrust. This could, for example, maintain the spacestation against the residual atmospheric drag at a lower altitude than they are presently constrained to.

Or, over a period of a number of months or years, if this thrust is continuous, this amounts to a very substantial Delta-V for systems in low earth orbit or in orbits where the magnetic field is high, such as Jupiter orbit.

(Fig. 7) The initial systems we have been looking at would use a small light-weight system with an available power supply of kilowatts to offset drag in low earth orbit. The power required could come either from a large spacecraft like spacestation or a large solar array, perhaps a utility solar array left in orbit between missions.

The payoff is that the fuel that would normally be required to keep a high drag object in orbit is eliminated. In fact, a kilowatt of power consumed in this way in orbit is the equivalent of something like a ton per year of fuel expended for orbit maintenance.

Carrying that a step forward, going to a larger more powerful system, a ten newton thrust system could be capable of continuous operation. This could provide altitude changes for something the size of the spacestation of several kilometers a day, or a hundred kilometers a day for a free flyer.

The total impulse, if you integrate this over a period of time, is extremely impressive.

TETHER THRUST GENERATOR

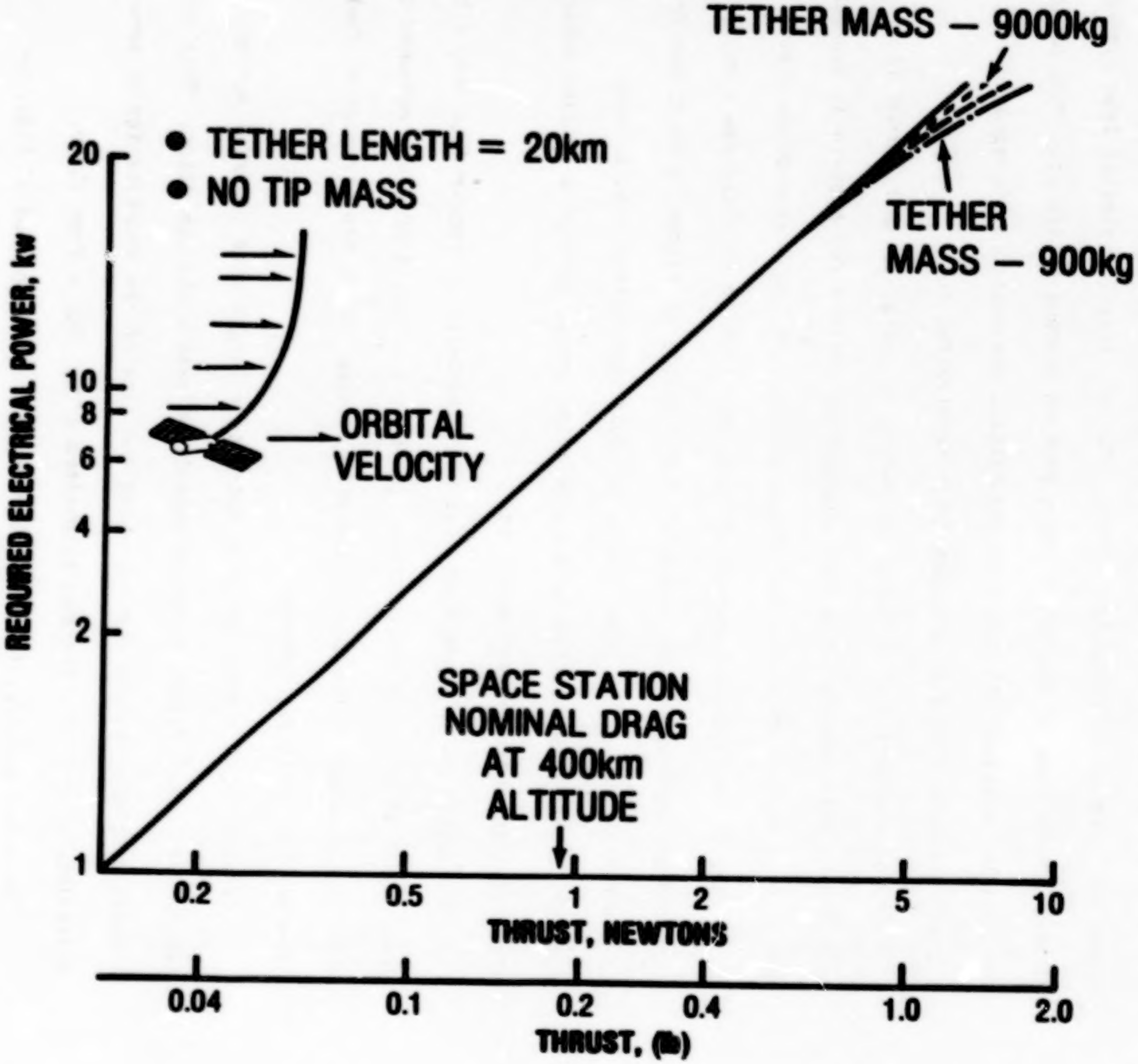


Figure 6

ELECTRODYNAMIC TETHER

RECOMMENDED APPLICATIONS

I. THRUST - USE WITH SOLAR ARRAYS IN LOW EARTH ORBIT TO OFFSET DRAG
- 100 KG SYSTEM PRODUCING .1 NEWTON THRUST
- 8 KW/N ELECTRIC POWER CONSUMPTION = .8KW
- ELIMINATES DELTA-V FUEL REQUIRED: >1,000 KG/YR
- KEEP 100 KW SOLAR ARRAY @ SPACE STATION ORBIT
  - INCREASE TO 200 KG SYSTEM @ 1-2 N THRUST
  - KEEP SPACE STATION + 100KW ARRAY IN <300 KM ORBIT ALTITUDE
  - NO ORBIT MAINT. FUEL REQUIRED; CONSUMABLES = < 60 KG/YR (ARGON)
  - USES 10-15 KW FROM 100 KW AVAILABLE

II. THRUST - USE FOR ORBITAL MANUEVERING PROPULSION
- 2,000 KG SYSTEM (PLUS 80 KW POWER SUPPLY: SOLAR, NUCLEAR, WHAT-EVER)
- 10 NEWTON THRUST - CONTINUOUS AS LONG AS POWER AVAILABLE
- ALTITUDE CHANGE
  - 7 KM/DAY - 200,000 KG (SPACE STATION)
  - 30 KM/DAY - 50,000 KG (PLATFORM)
  - 150 KM/DAY - 10,000 KG (FREE-FLYER)
- TOTAL IMPULSE: 864,000 N-SEC/DAY (194,000 LB-SEC/DAY)
  - 17 M/SEC/DAY - 50,000 KG (PLATFORM)
  - 86 M/SEC/DAY - 10,000 KG (FREE-FLYER, OMV, OR "TUG")
- ORBIT PLANE CHANGE: 30 DEGREE IN 6 MONTHS MAY BE POSSIBLE
- "FLY" ENTIRE SPACE STATION DOWN TO 200-250 KM ALTITUDE & MAINTAIN
- GROWTH VERSION: 200 N @ 1.6 MW, 20,000 KG + POWER SUPPLY

III. POWER STOREAGE - 100KW SOLAR ARRAY SYSTEM
+ 2,000 KG REVERSIBLE MOTOR/GENERATOR TETHER SYSTEM
- 60 KW THRUST DURING DAY (POWER STOREAGE AS ORBIT ENERGY)
- 100 KW POWER GENERATION DURING DARK
- TOTAL SYSTEM WEIGHT 40% OF CONVENTIONAL ARRAY WITH BATTERIES
- 10% REDUCTION IN SOLAR ARRAY SIZE
- 60% REDUCTION IN POWER PROCESSING HEAT REJECTION REQUIRED

Figure 7

Another application would be a reversible system, for power storage in place of batteries, which turns out to have a higher theoretical efficiency than charging and discharging of batteries. This application would require operating with about sixty kilowatts of power for thrust during the day , in effect, to "charge" the orbit by boosting the orbit altitude, then to use that excess orbit energy to generate a hundred kilowatts from the tether at night.

We calculate the total system weight as something on the order of forty percent of current state-of-the-art solar arrays and batteries. (see also fig 10). Elimination of batteries is where most of the weight comes from. However, the additional efficiency gives you both a reduction in the solar array size and a reduction in heat rejection that has to be handled by the system.

As a basis for these studies, we have produced something similar to a design curve for calculation of the performance of a system as a function of the net electrical power either put into the system as a motor, or taken from the system as a generator. (fig 8).

The numbers along the top of the plot are orbit drag. This will be one newton; ten newtons here. corresponding to one to a hundred kilowatts of power. You can convert that drag force to equivalent orbital drag power -- or propulsion energy -- which is shown along the bottom scale.

A given system -- this particular system is the 20-kilowatt reference aluminum tether system -- would then have a performance curve approaching an ideal -- a hundred percent efficient system would lie along the diagonal. For power generation, actual systems would be a curve somewhere below and to the right in the region marked "Generator Operation".

The upper left half of the plot will contain corresponding performance curves for operation as a motor.

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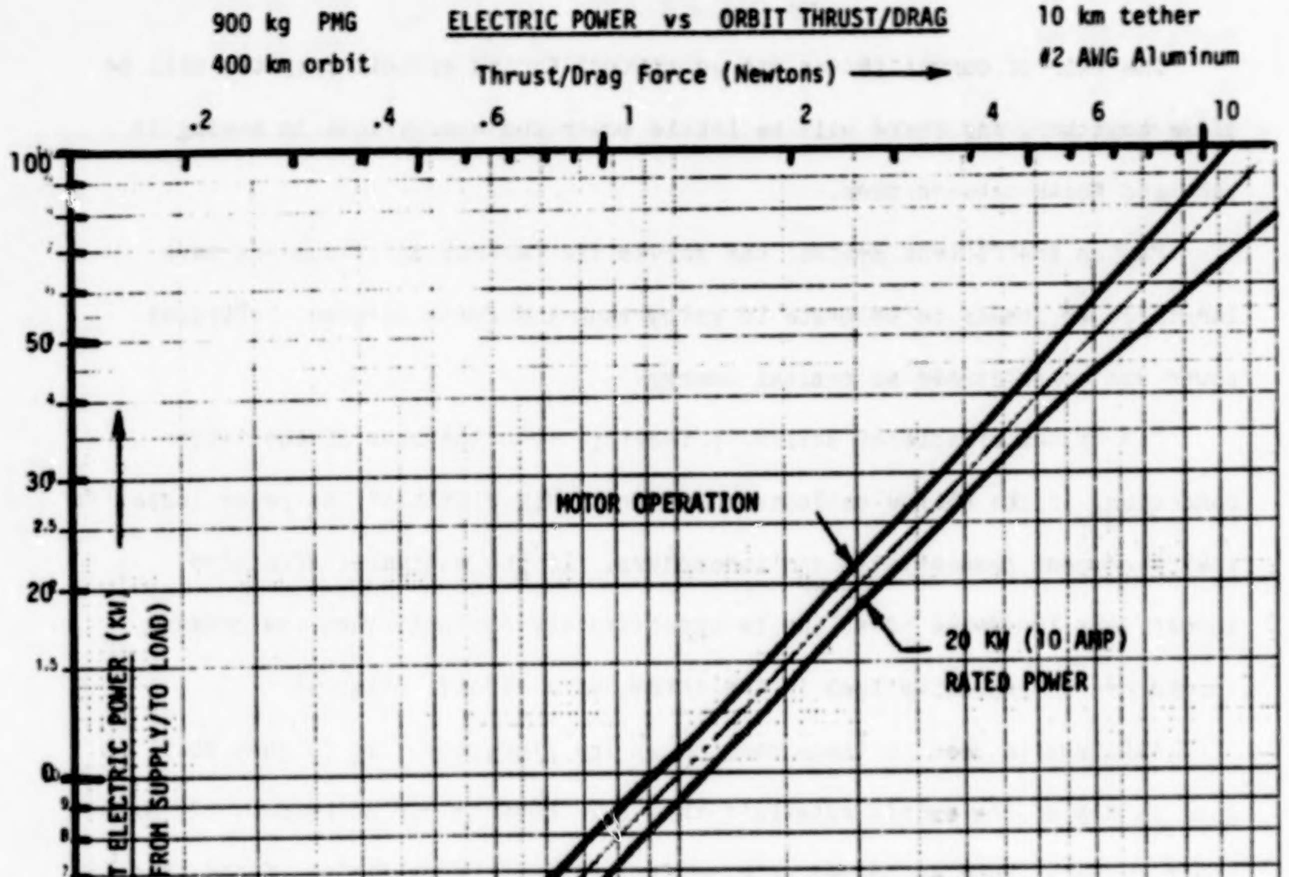

Figure 8

The pair of curves (motor and generator) for an efficient system will be close together. and there will be little power and energy lost in moving it back and forth between them.

For an inefficient system, the curves lie farther apart and you have larger power losses to tolerate in going back and forth between electrical power and power stored as orbital energy.

The system efficiency scales, primarily, with the mass of the tether conductor, if the hollow cathodes can effectively eliminate the power losses in making current contact with the ionosphere. If the estimated effective ionospheric impedance of an ohm is approximately correct, then the primary losses are in resistive loss in the tether wire itself. (Fig. 9)

Aluminum is used in these designs as the conductor. It is just about as good as any of the exotic materials that have come to our attention. It is about twice as good as copper on a conductivity per mass basis. Since it's mass in orbit that you have to pay for, and the performance of the system turns out to be almost directly proportional to mass, aluminum looks best for most tethers.

If you want -- if you were curious about how the plot of performance for the nine thousand kilogram system could be extrapolated out here beyond a thousand kilowatts -- if you shifted all these scales by an order of magnitude and made this (full scale) ten thousand kilowatts, then this (the 900 kg curve here) would be the nine-thousand kilogram performance plot. To first approximation. There are some minor differences in the power losses in the hollow cathodes. Eventually it becomes significant. And the ionospheric losses eventually become significant.

For a quick illustration, I'll discuss the replacement of batteries.

This is a plot (fig 10) of resources necessary to operate a 100 KW solar

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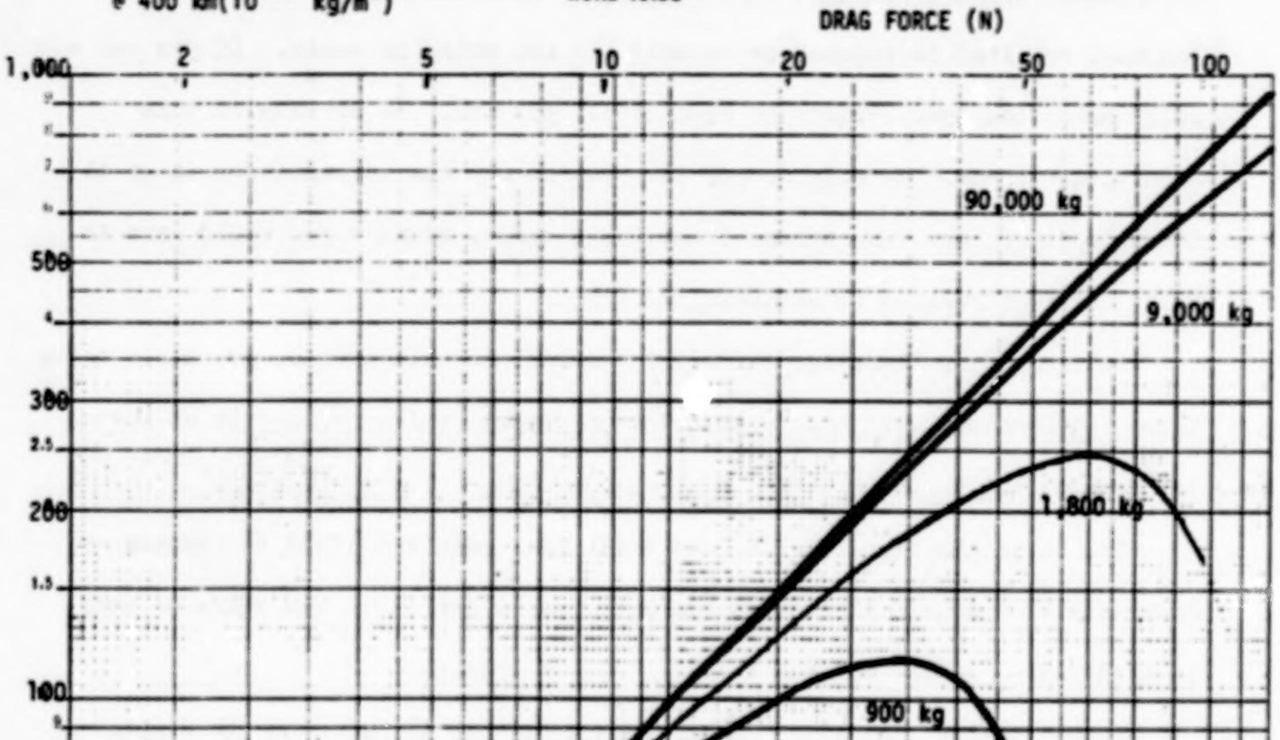
20 km (DUAL) PMG
@ 400 km(10^{-11} kg/m^3)

PERFORMANCE
vs
WIRE MASS

POWER GENERATOR



array power system. This is versus altitude from 500 kilometers down to 200, and fuel required to reboost or to maintain the thing in orbit. If you ran a solar array and used rockets to reboost it, you would be working on this prohibitive curve. This is one of the reasons why the spacestation is up at 500 kilometers, not down around Shuttle altitudes, because you would have to carry too much fuel up to maintain the orbit.

But, by using these two different versions of this system, you could bring these requirements well down within the practical region to operate at lower orbits with the thing.

Or, up at the higher orbit, the total mass required could be reduced -- immediately -- or, in the second concept, over a period of ten years -- very substantially beyong what the existing system provides.

Then, finally. let's get away from the mundane and move out to Jupiter for a while, to illustrate the power of this thing.

Jupiter gravity is very strong. Fig. 11 shows the total orbit energy versus distance from Jupiter, in Jupiter radii. The scale is from the surface of Jupiter (at 1.0 R_J) logrithmic thru one hundred Jovian radii.

The major moons, Io through Callisto, are shown as points along the plot of orbit energy vs. distance. Also plotted here (I hope this isn't confusing) is orbit velocity and magnetospheric corotation velocity versus distance. The vertical axis, for orbit energy, is expressed in units of megajoules per kilogram, up to a thousand (on the left side). On the right side, I converted this to kilowatt hours per kilogram.

The energy to go even to the moons is very high compared, for example, with the energy required to launch from the surface of the earth to a low earth orbit (about 8 KWHR/kg; for reference this is marked on the plot, near the energy level of Callisto's orbit).

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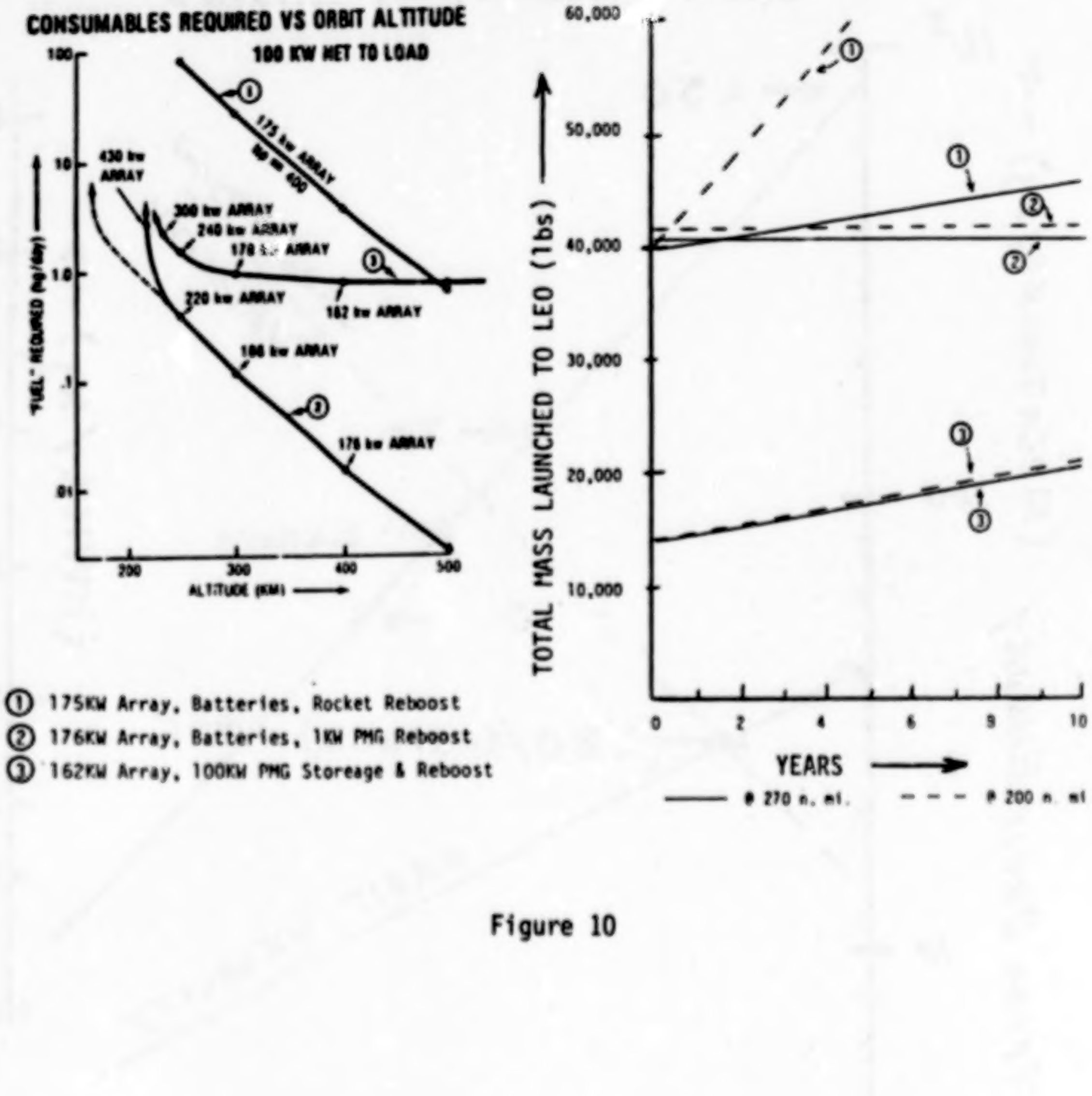


Figure 10

JUPITER
ORBIT ENERGY vs RADIUS

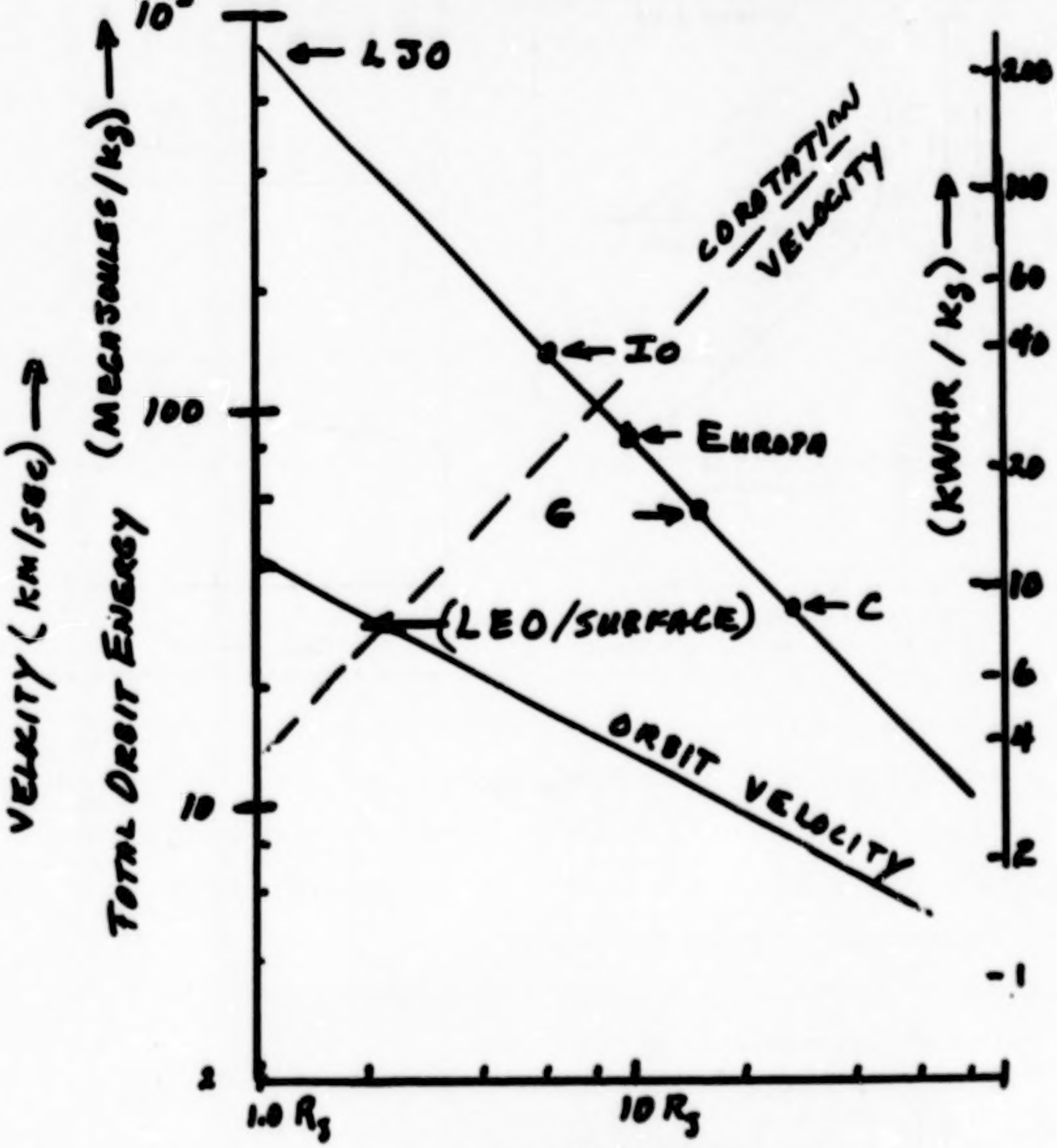


Figure 11

The energy to go to a very low Jupiter orbit is prohibitive for any normal propulsion system.

Yet, a system like some of these large tether systems -- if it operates like it should, and without considering the corotation of the Jovian magnetosphere -- if you express this gravity potential in kilowatt hours per kilogram required to propel the thing, it's something like a little over 200 kilowatt hours per kilogram, well within the capability of a nuclear power supply.

This has two nice applications.

With today's technology, we can get to the moons by doing gravity bouncing back and forth and get into orbits there. But the power is prohibitive to go from there to, say, a low survey orbit (or, later on with fleets of manned vehicles; perhaps to scoop methane from the top of the Jupiter atmosphere to produce gasoline or whatever is important, when that day comes). You can get down there using a tether by dissipating the energy. You don't even have to bring a power supply. All you have to do is use up the excess energy in a resistor or a big radio transmitter or something to get down to the surface.

To come back, if you brought a nuclear reactor with you, those sort of power densities should be available, and this is one way that you might be able to go to the surface of Jupiter and get back with a crew, or get back with a sample, or bring a commercial payload with you, depending on how far in the future you want to project your operation.

The second application uses the magnetospheric corotation effects, and requires that condition to be satisfied.

Since the reference frame for VXB induced voltage and IXB force on the tether is the frame moving with the magnetosphere, the "drag" force produced under tether power generation is calculated with respect to the local corotation velocity. This becomes negative at distances beyond the synchronous rotation orbit, resulting in acceleration of a spacecraft in circular orbit by the same reaction forces that produce deceleration closer to the planet. The principle is the same as Alfven's hypothetical solar wind engine.

In that case, a space factory could be located at the synchronous orbit (about 2 R_J) with two power generating tethers attached. One tether deployed away from the planet would produce a "drag" accelerating the space factory to offset the decelerating "drag" of the second tether deployed downward. The net effect is that power could be produced continuously, with no net change in the orbital altitude. The system would be effectively tapping the rotational energy of the planet to produce electrical power, in quantities limited only by the corotational coupling of magnetosphere to planet.

Operation of such a system around other planets, for example in Earth geosynchronous orbit or a lunar anchored orbit in the solar wind, will require development of superconducting tether wire to be feasible. However, the Jupiter magnetic field is sufficiently strong at synchronous orbit to produce adequate induced voltage and IXB forces to operate with conventional conductors.

N86-28416

TRANSPORTATION

Georg von Tiesenhausen
Marshall Space Flight Center, NASA

C-3

I'd like to summarize where we are today in tether transportation, how we got there, and what we have learned.

I received a notice from my co-speaker, Dr. Gianfranco Bevilacqua, that he has another commitment and will not come. So I guess we can save some time.

We started off after the last workshop with many concepts in tethered transportation. I will show you briefly the sequence of studies through which these concepts had to pass in order to recognize the survivors that are valuable and practical to carry out (Chart 3).

These four steps were used over a time period of three years. Initially, theoretical engineering feasibility and technology requirements were determined. Then the survivors of that effort went into step two in the analysis of promising candidates. Those survivors went into the third phase: engineering design and cost benefit analysis. We are in that phase with several concepts. Finally, those survivors enter into the demonstration mission definition phase.

From some 30 concepts we got down to four, using these phased studies. The technologies that we defined during the studies cover areas listed here on the next chart (Chart 4). In front of all other technologies are tether materials and configurations. Obviously, the tether itself is the heart of the whole system. Then instrumentations, both engineering and science, a very important area that is still in evolution.

Systems Dynamics Simulation

The numerous simulation programs, which cover the many applications are continuously expanding to include demonstration missions.

Atmospheric aerothermodynamic technology is next. You will hear about that a little bit later.

You have heard about hollow cathodes, and across the board, critical component technology. One critical component, just to mention an example, is the deployment brake which has the size of a large aircraft brake and has to dissipate some five hundred or so kilowatt hours over a deployment period, deploying the orbiter from the Space Station, for example.

Now the demonstrations. We entered the demonstration definition phase with several concepts. First, the demonstration objectives; whatever critical issues exist, the solutions to these must be demonstrated (Chart 5). Second, and very important, we have to be able to afford these demonstrations. They cannot be too expensive, which means they have to be simple and concentrate on the issues.

We like to use as much available hardware at the end of the tether as possible, where we can attach our required instrumentation. We have a number of available instrument carriers. Among others, there is a re-entry vehicle, which has been used before, and which we study to use as a carrier between a Space Station and the ground, eventually. So, when the Space Station has some material or biological specimens and does not want to wait three months for the next orbiter to come, this re-entry vehicle can take it down. So the entry vehicle is a very important potential payload.

Then we want to have a short development time, which goes together with simplicity and affordability. Say two years, or three maybe.

Our transportation studies have covered two kinds of deployments. First, we studied steady state deployment (Chart 6). It's like the TSS, nearly vertical. It takes a very long time to deploy and involves relatively high tether tension.

A few special studies concentrated on dynamic deployment (Chart 7) where you start your deployment in an almost horizontal direction under a very shallow angle which allows you high deployment rates under very low tension. Momentum transfer here occurs by libration. You release the payload by having a tether swing through the local vertical at which time the payload is disconnected.

We can have payloads that we can retrieve and payloads without retrieval. We have under development a disposable tether deployment system, which weighs much less than one that is capable of retrieving. I have a few words about that later.

In order to study tethered transportation benefits, we use specific payloads. This doesn't necessarily mean that those future payloads will be launched by tether, but they are potential candidates. The advantage was that we know everything about those payloads: their masses, their characteristics, and their conventional deployment methods. Now we have valid comparisons between those and the tether deployment.

The first example was the SSUS spacecraft, which weighed some 6800 kilograms (Chart 9). Our study showed that, in a tethered deployment of this system, we can save almost 2300 kilograms of OMS propellant on the orbiter, because the orbiter doesn't need to go up to that altitude. And the spacecraft itself, the SSUS, saves some 4000 kilograms of propellants.

Another example where all the numbers are known is the AXAF, the Advanced X-Ray Astrophysics Facility (Chart 10). We tried to find out, if you launched that one from the end of a tether, if this facility would be able to go into a 320 nautical mile circular orbit. What we found out was, if you put the orbiter in an elliptical orbit, 290 x 180 nm, and use about a 33 nautical mile long tether, then the payload, the AXAF, goes exactly into its 320 nautical mile circular orbit, while the orbiter itself goes into a 287 to 100 nautical mile orbit with plenty of time to close the cargo doors for reentry. The OMS propellant saved would be some 3300 kilograms.

Another typical example where all the numbers are known is the space telescope. I will just point out the important points on this chart (Chart 12).

The space telescope also needs to go into this 320 nautical mile circular orbit, but with a tether we can put it 50 nautical miles higher.

With a 40 nautical mile tether, the orbiter only needs to go into a 102 x 330 nautical mile eccentric orbit. In doing that, we have propellant savings of 7600 lbs. Sorry about the mixture of units. On the payload side, since the orbiter has to go into a lower orbit than the payload, it has an excess capacity of 8000 lbs of cargo weight.

These are typical examples where we showed the advantages of tethers to transportation.

Now I mentioned at the beginning that, from some thirty concepts we ended up with four transportation concepts, which we have under study now with regard to cost benefits (Chart 13). These are the four: a tethered orbiter de-boost from the Space Station, an OTV boost up from the Space Station, a science platform on a tether with a possible micro-g lab moving in between platform and station, and a tethered boost of payloads from the orbiter, where I just gave you some examples. This is the deployment of the orbiter from the Space Station (Charts 14, 15). We have a dual deployment mechanism in the Space Station that allows deployment of payloads down and up.

What you see on top is an OTV. These two spacecraft can be launched or deployed alternately, within a few days or a week. In that case, you see, the Space Station is the momentum storage facility. It stores angular momentum. Since the Space Station would go up into inaccessible highs by deploying an orbiter, alternate OTV launches will maintain the proper altitude for the station.

The engineering approach was such that the two moments are equal, so the station stays essentially where it was. The benefit of using this on a Space Station is considerable (Chart 16). Through the early 90's we can save eight to ten thousand kilograms of Shuttle, Station and OTV propellant. Later, in the second half of the decade, we can save between 30 and 50 thousand kilograms of propellant annually. The difference between the first and second half of the 90's results from traffic and all sorts of activity differences. The orbital drag will be much higher in the later 90's than the early 90's and would consume more drag make-up propellants.

Another effort that's going on covers automated procedures for tethered rendezvous (Chart 19). I showed you the deployment of an orbiter from a Space Station before. You can envision that an orbiter now docks remotely at the end of a tether below the Station, avoiding any dynamics involved in docking directly to the Station. That's a very tricky maneuver.

We have an effort going on to automate this process because of the short time available to acquire the connection. I have listed next an area that doesn't seem to fit into transportation. It is more a constellation, but I'd like to mention it, anyway.

We studied a three-mass linear constellation. The center mass is a spacecraft containing essentially a big capacitor. You have an electrodynamic tether going up and one going down, with space plasma contactors. This is, hopefully, an efficient communications system for ULF and ELF frequencies.

Then one of our major efforts going on is an expendable tether system payload mission analysis. For our expendable tether system, we want to demonstrate the deployment of certain payloads and verify the disposable tether system.

This is the tethered rendezvous (Chart 20) -- the remote rendezvous — that I mentioned. We have an OTV at the end of a small end effector deployed from the Space Station. This process is being analyzed for an automated approach.

This (Chart 21) is a picture of the ULF-ELF antenna. In the center is the capacitor-spacecraft, then we have the up and down electrodynamic tether. For instance, it may work such that for a millisecond the upper tether generates power which is stored in the capacitor. And during the next millisecond the energy is emitted from the lower conducting tether.

There is a study underway to provide the systems approach here and to assess the possibilities of a system like this.

This (Chart 22) is a flight experiment that has been approved recently. It is the disposable tether system that is deployed out of a so-called GAS can with a payload that can be deployed about 20 or so kilometers and then disconnected.

We have found out that even a disconnected payload can be recovered, under certain conditions, by the Shuttle. Okay. What have we learned of all this? (Chart 26)

One of our concerns are tether issues...what can we do to reduce tether recoil after payload release or breakage? How can we increase durability of the tether so it can be used many times? An what can we do about debris collision hazards?

We have to review statistics and probabilities and come up with tether configurations that are less vulnerable than a round tether. Maybe a ribbon or something.

Now let me say a few words about energy management. During deployment, we generate about 15 to 20 kilowatt hours of energy on the orbiter deployer that have to be dissipated. On the Space Station it is up to 500 kilowatt hours. That's the main issue.

For retrieval, we need about two kilowatt hours of work on the orbiter, and sometimes up to 30. On the Space Station, we require some 70 kilowatts of power.

Of course, we must discuss the impacts. Everything we do on the Space Station induces g levels. What can we do about it? About 10^{-4} g may be induced by a number of tether operations.

Structural stress must be discussed because the tether has to be attached somewhere. And the tether tension has to be carried into the structure. Where do we put the deployer system? We have to reduce volume and space. We need energy. And we have to dispose of energy. We have to define that soon. We have made a lot of progress.

There are certain conditions we have to follow in order to have benefits in the first place (Chart 25). The deployment system has to be lightweight. If I saved 3,000 lbs of propellant and have to carry a deployment system that weighs 6,000 lbs, I haven't saved much. So a disposable tether payload deployment system is under development, weighing only a few hundred pounds.

It is practical to deploy upward payloads toward the end of the orbital mission. You save propellants for the re-entry. Especially if you have one single payload among several that needs to go into a higher orbit, then the tether is of a major benefit. Otherwise, the orbiter has to change its orbit just for one payload.

The maximum payload you can deploy upward from the orbiter is about 12,000 kilograms from a normal orbital altitude. That's what we have learned.

And I'd like to just say a few words again about the expendable tether system. It's under development. It's a candidate for our demonstrations. Because the TSS system is busy for quite a number of years, we have to have our own deployer. And we are fortunate to have a good idea now under development which was originated by Joe Carroll, whom you have listened to before.

It is a low tether tension deployment, almost horizontal which swings in to the vertical. Payload release is at the vertical. We are defining flight experiments, and we have certain payloads for these flights under investigation.

And, finally, assessing the benefits (Chart 23). We can deploy up to 12,000 kilogram payloads from the orbiter. We can save up to 7500 kilograms of propellants on the orbiter. We can launch and deploy from the Space Station up to a hundred tons of payload.

By the way, the Space Station mass, I think it has doubled or is about to double. I don′t know exacatly, but the heavier the Space Station, of course, the better are tether operations.

In the early 90′s we can save up to nine thousand kilograms of propellants annually. And, in the late 90′s, up to 50,000 kilograms. We think this is a remarkable possibility of tethered transportation.

Thank you very much.

ORGANIZATION: PROGRAM DEVELOPMENT	MARSHALL SPACE FLIGHT CENTER	NAME: GEORG von TIESENHAUSEN
CHART NO.: 4644–85		DATE: OCTOBER 1985

TETHER TRANSPORTATION

PRESENTED AT THE

APPLICATIONS OF TETHERS IN SPACE WORKSHOP

VENICE, ITALY

OCTOBER 15–17, 1985

CHART 1

TETHERED TRANSPORTATION

TETHERED SPACECRAFT CONSTELLATIONS AND PLATFORMS

ELECTRODYNAMIC INTERACTIONS OF TETHER SYSTEM

ELECTRODYNAMIC TETHER COMPONENTS

TETHER TECHNOLOGY AND TEST

SCIENCE AND APPLICATIONS

GRAVITY UTILIZATION THROUGH TETHERS

ADVANCED CONCEPTS DEVELOPMENT

TETHER APPLICATION IN SPACE CATEGORIES

CHART 2

1) THEORETICAL AND ENGINEERING FEASIBILITY AND TECHNOLOGY REQUIREMENTS

2) IN–DEPTH ANALYSIS OF PROMISING CANDIDATE APPLICATIONS

3) ENGINEERING DESIGN AND COST/BENEFIT ANALYSIS OF SELECTED APPLICATIONS

4) DEMONSTRATION MISSION DEFINITION OF SELECTED APPLICATIONS

STUDY PLANNING

CHART 3

1) TETHER MATERIALS AND CONFIGURATIONS

2) TETHER APPLICATIONS ENGINEERING INSTRUMENTATION

3) TETHER APPLICATIONS SCIENCE INSTRUMENTATION

4) TETHER SYSTEM DYNAMICS/ORBITAL MECHANICS SIMULATION

5) ATMOSPHERIC/AEROTHERMODYNAMIC TECHNOLOGY

6) HOLLOW CATHODE TECHNOLOGY

7) TETHER APPLICATIONS CRITICAL COMPONENT TECHNOLOGY

TECHNOLOGY PLANNING

CHART 4

1) **CAPABILITY OF FULFILLING FLIGHT OBJECTIVES**

2) **AFFORDABILITY**

3) **SIMPLICITY**

4) **MAXIMUM USE OF AVAILABLE PAYLOAD HARDWARE WITH MINIMUM MODIFICATIONS**

   - **AVAILABLE INSTRUMENT CARRIERS**

   - **AVAILABLE REENTRY VEHICLES**

5) **MINIMUM DEVELOPMENT TIME (~ 2 YEARS)**

DEMONSTRATION PLANNING CRITERIA

CHART 5

ORGANIZATION: PROGRAM DEVELOPMENT	MARSHALL SPACE FLIGHT CENTER	NAME: GEORG von TIESENHAUSEN
CHART NO.: 4645-85	**TETHER TRANSPORTATION**	DATE: OCTOBER 1985

DEPLOYMENT AND RETRIEVAL OPTIONS

- **STEADY STATE DEPLOYMENT – BASIS FOR MOST STUDIES SO FAR**
  - DEVELOPMENT IS NEARLY VERTICAL
  - LOW DEPLOYMENT RATES
  - HIGH TETHER TENSION (INCREASES WITH TETHER LENGTH)
  - MAY OSCILLATE ABOUT VERTICAL

ORGANIZATION:
PROGRAM
DEVELOPMENT

CHART NO.:
4647–85

MARSHALL SPACE FLIGHT CENTER

TETHER TRANSPORTATION

NAME:
GEORG von TIESENHAUSEN

DATE:
OCTOBER 1985

DEPLOYMENT AND RETRIEVAL OPTIONS

- DYNAMIC DEPLOYMENT – BASIS FOR SPECIAL STUDIES
  - DEPLOYED PRIMARILY AT CONSIDERABLE ANGLE TO LOCAL VERTICAL
  - HIGH DEPLOYMENT RATES
  - LOW TETHER TENSION

  LIBRATING – DISPOSABLE TETHER PAYLOAD DEPLOYMENT STUDY

  ROTATING – NASA STUDY ON ROTATING DUMBBELL DYNAMICS

  PUMPING – TO BE STUDIED IN THE FUTURE
- WITH RETRIEVAL – TETHERED REMOTE DOCKING STUDY

  CONTROL LAWS + PROPULSION (DEPENDING ON TETHER MEASUREMENT ACCURACY)
- WITHOUT RETRIEVAL – EXPENDABLE TETHER DEPLOYMENT SYSTEM UNDER DEVELOPMENT

  RETRIEVAL PRACTICAL UNDER CERTAIN CONDITIONS

CHART 7

SSUS ORBITER LAUNCH REQUIREMENTS

- **PAYLOAD MASS = 6800kg**
- **LAUNCH DURING PAYOUT**
- **SPIN UP AFTER SEPARATION**
- **3 KW VARIABLE SPEED RETRIEVAL MOTOR**
- **HEAT SINK (AIRCRAFT STYLE) BRAKE**

DESIGN SPECIFIC

TETHER LENGTH – 125KM

MAX TENSION – 1780 N

MAX TETHER VELOCITY – M/S – 366

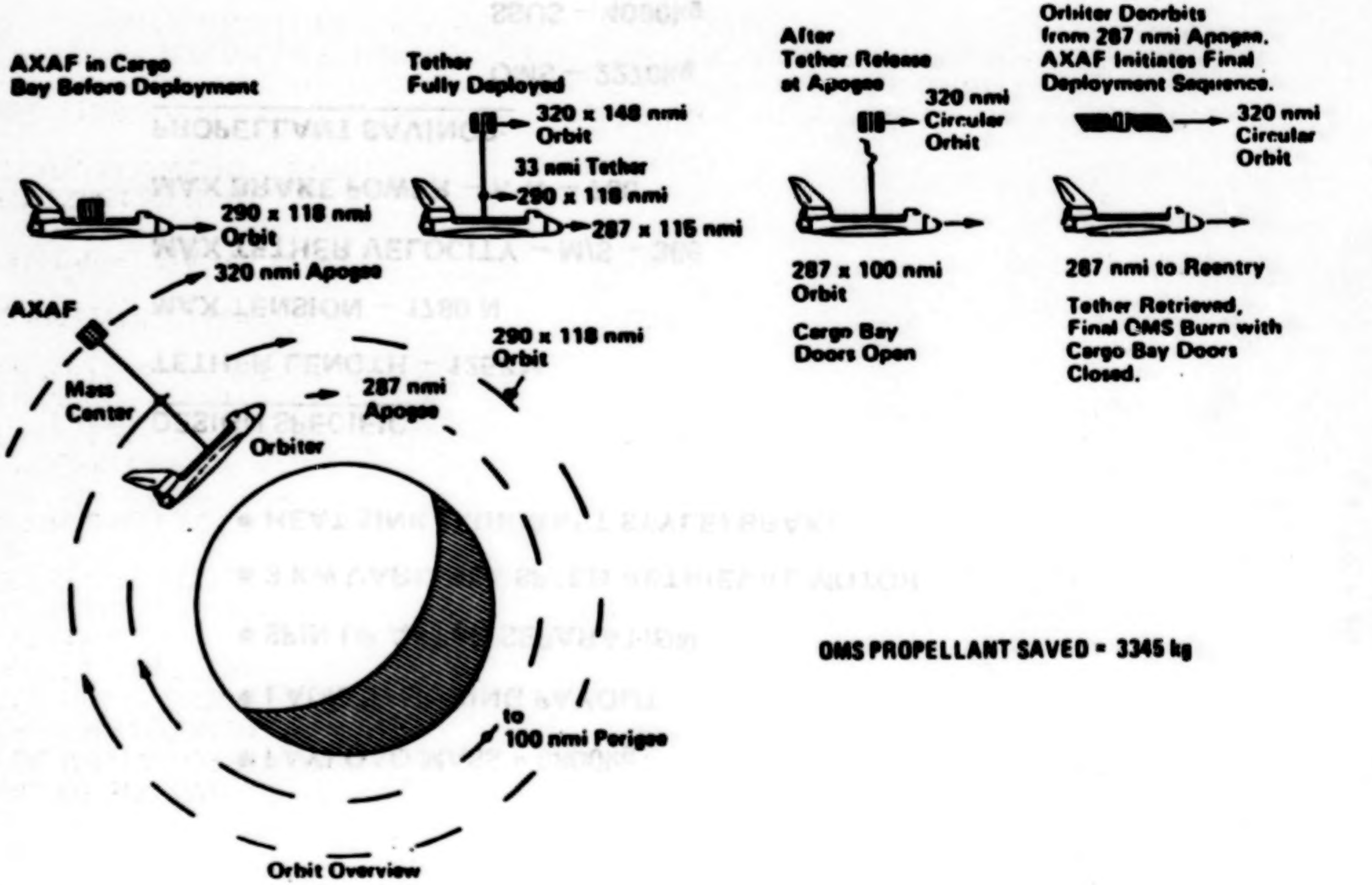
MAX BRAKE POWER – K W – 700

PROPELLANT SAVINGS:

OMS – 2270kg

SSUS – 4090kg

CHART 9


AXAF in Cargo Bay Before Deployment
290 x 118 nmi Orbit
Tether Fully Deployed
320 x 148 nmi Orbit
33 nmi Tether
290 x 118 nmi
287 x 115 nmi
After Tether Release at Apogee
320 nmi Circular Orbit
287 x 100 nmi Orbit
Cargo Bay Doors Open
Orbiter Deorbits from 287 nmi Apogee. AXAF Initiates Final Deployment Sequence.
320 nmi Circular Orbit
287 nmi to Reentry
Tether Retrieved, Final OMS Burn with Cargo Bay Doors Closed.
320 nmi Apogee
AXAF
290 x 118 nmi Orbit
287 nmi Apogee
Mass Center
Orbiter
to 100 nmi Perigee
Orbit Overview

OMS PROPELLANT SAVED = 3345 kg

AXAF DEPLOYMENT SEQUENCE/SHUTTLE RESPONSE

CHART 10

TETHER ORBIT INSERTION OF SPACE TELESCOPE

	DIRECT INSERTION METHOD	TETHER INSERTION METHOD
ST FINAL ORBIT (NMI)	320 X 320	370 X 370
(1) SHUTTLE INITIAL ORBIT (NMI)	320 X 320	130 X 334
TETHER LENGTH (NMI)	– – – –	40
(2) SHUTTLE FINAL ORBIT (NMI)	320 X 320	102 X 330
OMS PROPELLANT (LB)		
LOADED	25100	25100
REQUIRED, WITH MARGIN	25100 (EST.)	12500 (EST.)
OFF–APOGEE DEORBIT ALLOWANCE	– – – –	5000 (MAX)
EXCESS OMS PROPELLANT	0	(3) 7600 (EST.)
SPACE TELESCOPE WT (LB)	25500	25500
ST ASE WT (LB)	2500	2500
TETHER DEPLOYER SYSTEM (LB)	– – – –	8000
TETHER RETRIEVAL POWER BATTERIES (LB)	– – – –	4000
CARGO WEIGHT LOADED (LB)	28000	40000
CARGO WEIGHT MARGIN (LB)	0	(3) 8000 (EST.)
TETHER TENSION (LB)	– – – –	750
ST RETRIEVAL ENERGY (kWh)	– – – –	31

NOTES:
(1) SHUTTLE DIRECT INSERTION TO APOGEE OF INITIAL ORBIT
(2) SHUTTLE DIRECT DEORBIT FROM APOGEE OF FINAL ORBIT
(3) BASED ON PRELIMINARY ESTIMATE OF SHUTTLE PERFORMANCE WITH ABORT RETURN FROM INITIAL ORBIT.

CHART 12

MARTIN MARIETTA

4806—85

SELECTED TETHER APPLICATIONS IN SPACE STUDY

PHASE I COMPLETED:

SURVEY AND ASSESSMENT OF 26 TRANSPORTATION (AND A FEW CONSTELLATION) CONCEPTS.

PHASE II COMPLETED:

DETAIL ANALYSIS OF FOUR SURVIVING CANDIDATES:

(1) TETHERED ORBITER DEBOOST FROM SPACE STATION

(2) TETHERED OTV BOOST FROM SPACE STATION

(3) TETHERED SPACE STATION SCIENTIFIC PLATFORM

(4) TETHERED PAYLOAD BOOST FROM ORBITER

PHASE III STARTED:

ENGINEERING DESIGN AND COST/BENEFIT ANALYSES OF THE PHASE II CONCEPTS.

CHART 13

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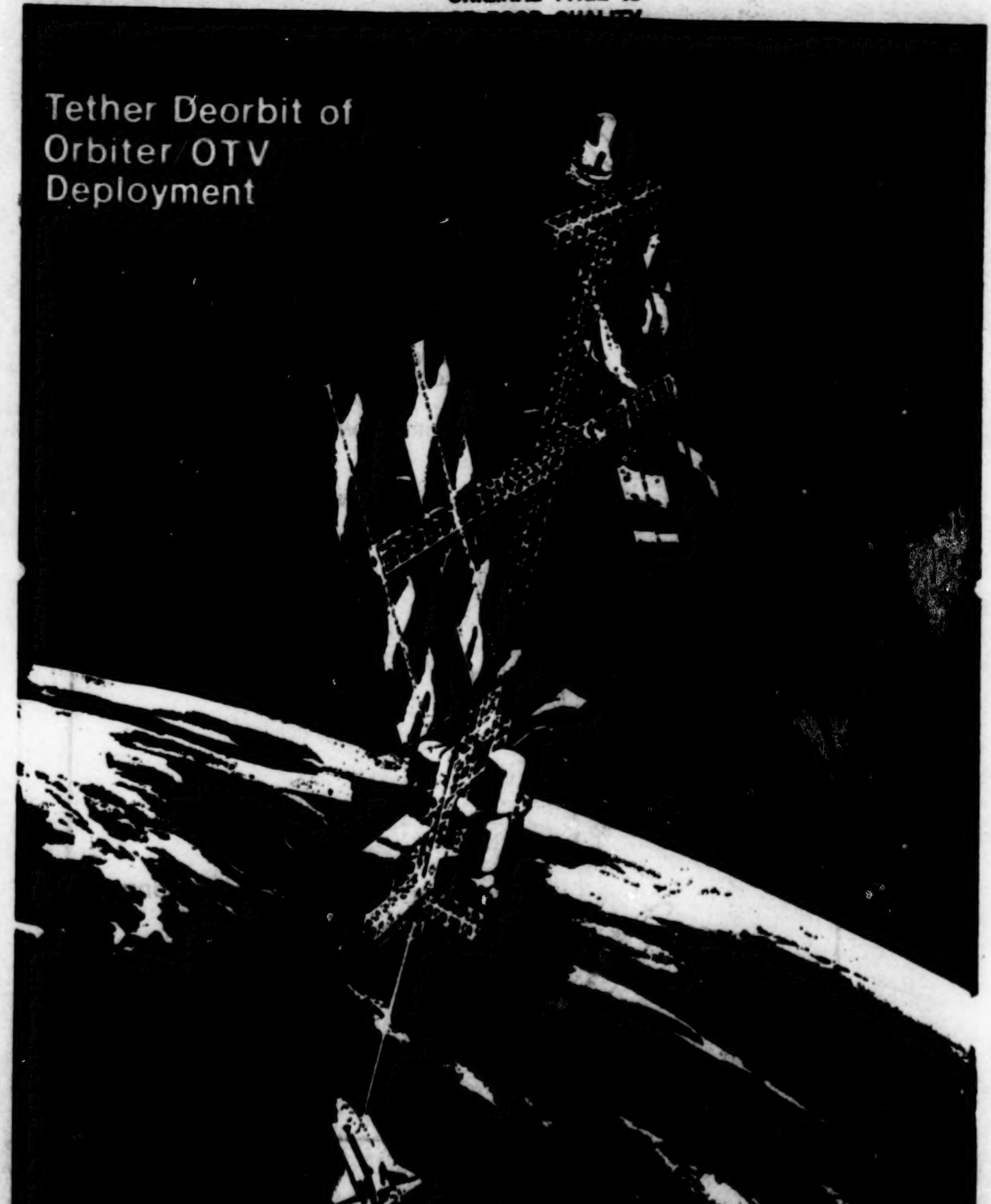

Tether Deorbit of Orbiter/OTV Deployment

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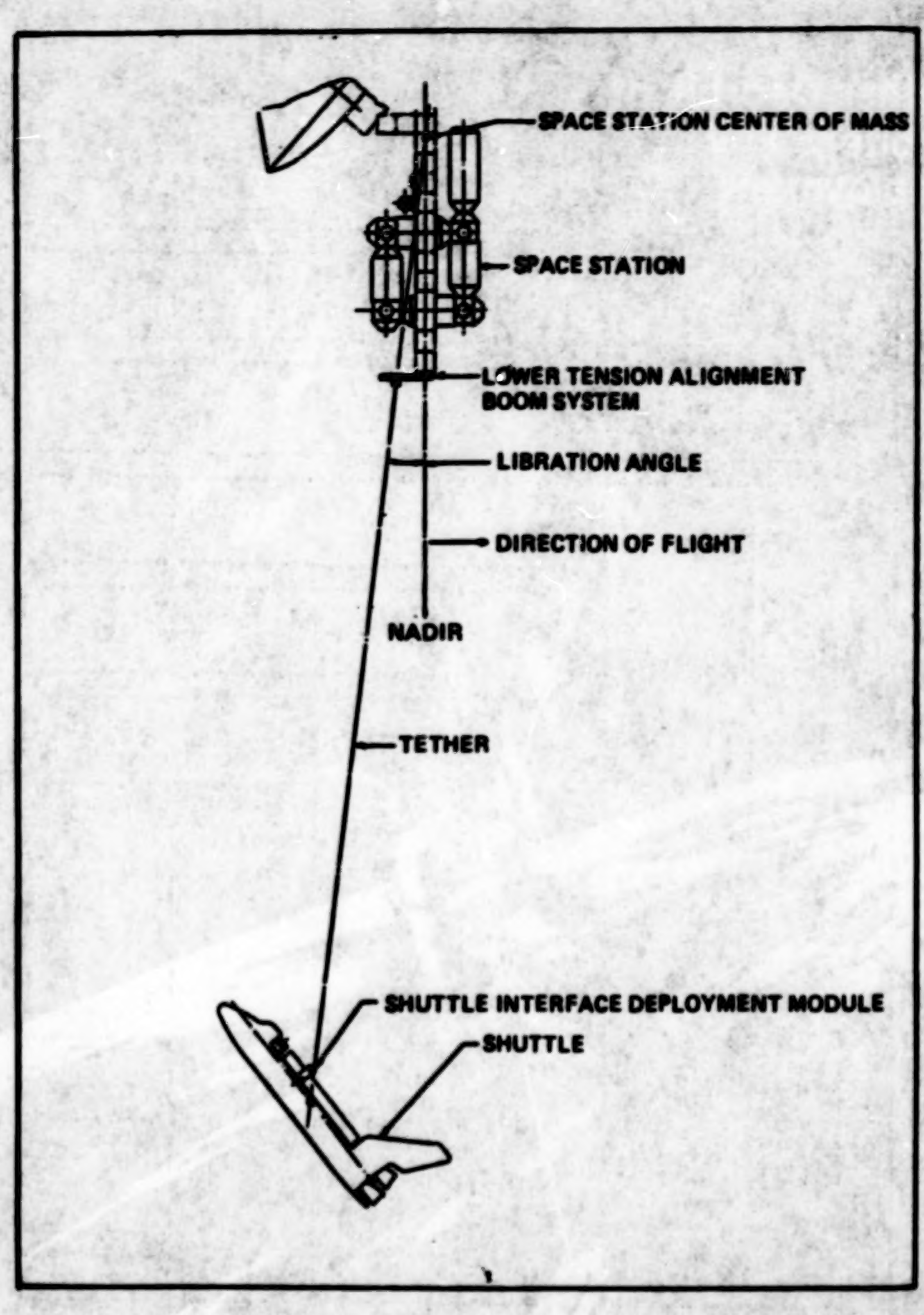
CHART 14


SPACE STATION CENTER OF MASS
SPACE STATION
LOWER TENSION ALIGNMENT BOOM SYSTEM
LIBRATION ANGLE
DIRECTION OF FLIGHT
NADIR
TETHER
SHUTTLE INTERFACE DEPLOYMENT MODULE
SHUTTLE

SPACE STATION/SHUTTLE ATTITUDE DURING DEPLOYMENT

CHART 15

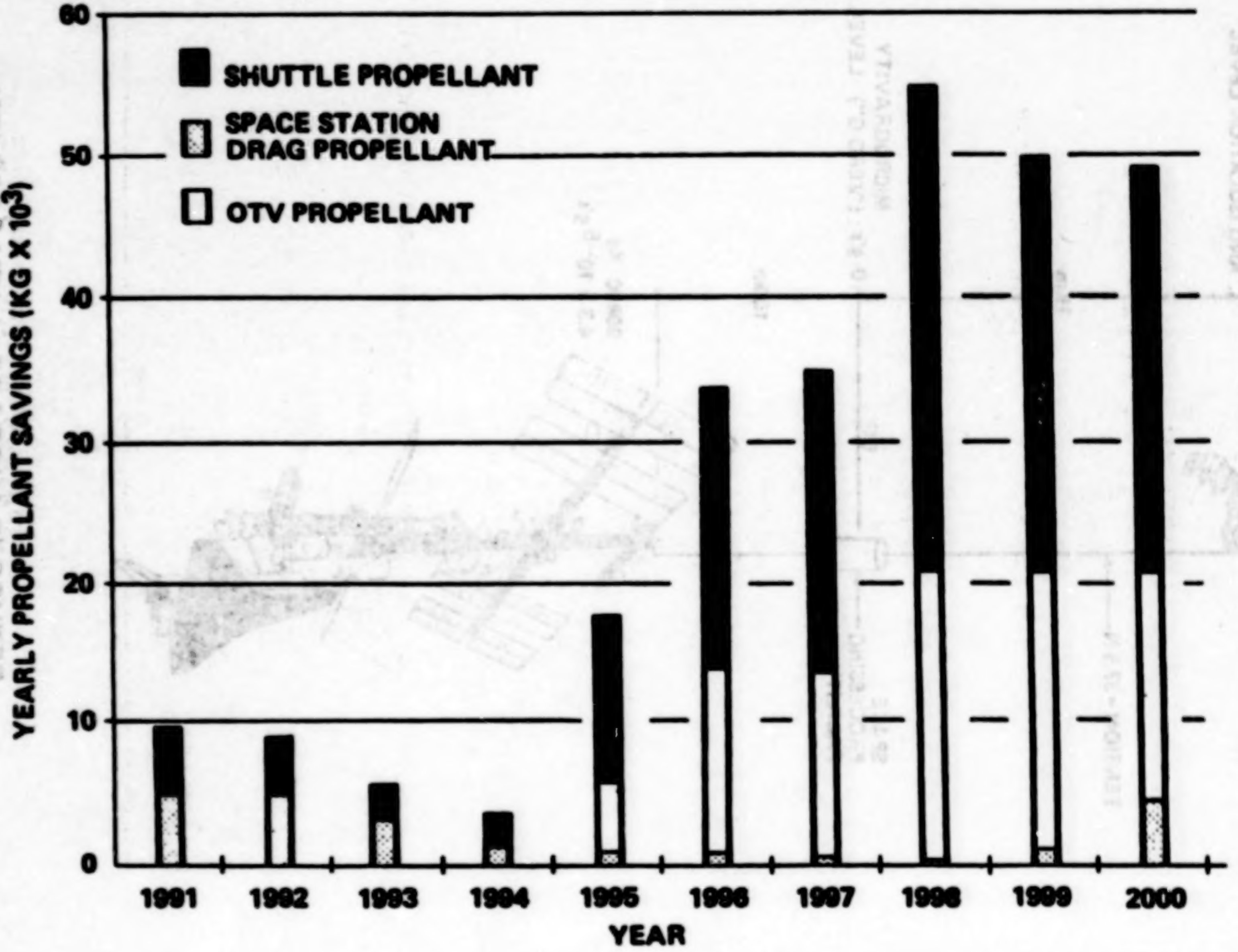
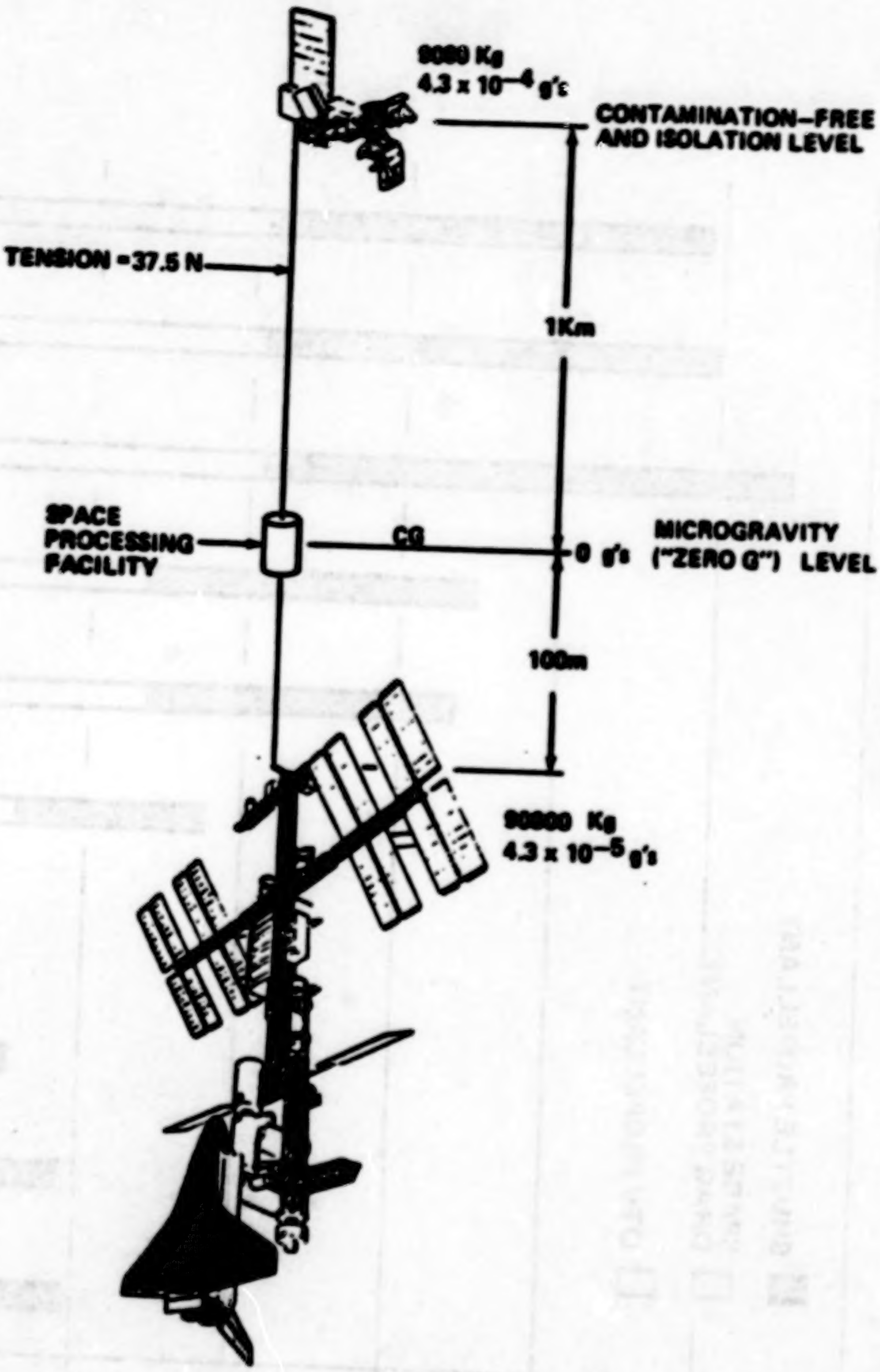


CHART 16

FIGURE . TETHER BENEFITS IN TERMS OF ANNUAL PROPELLANT SAVINGS


9000 Kg
4.3×10^{-4} g's
CONTAMINATION–FREE AND ISOLATION LEVEL
TENSION = 37.5 N
1Km
SPACE PROCESSING FACILITY
CG
0 g's
MICROGRAVITY ("ZERO G") LEVEL
100m
90000 Kg
4.3×10^{-5} g's

TETHERED MICROGRAVITY FACILITY

CHART 17

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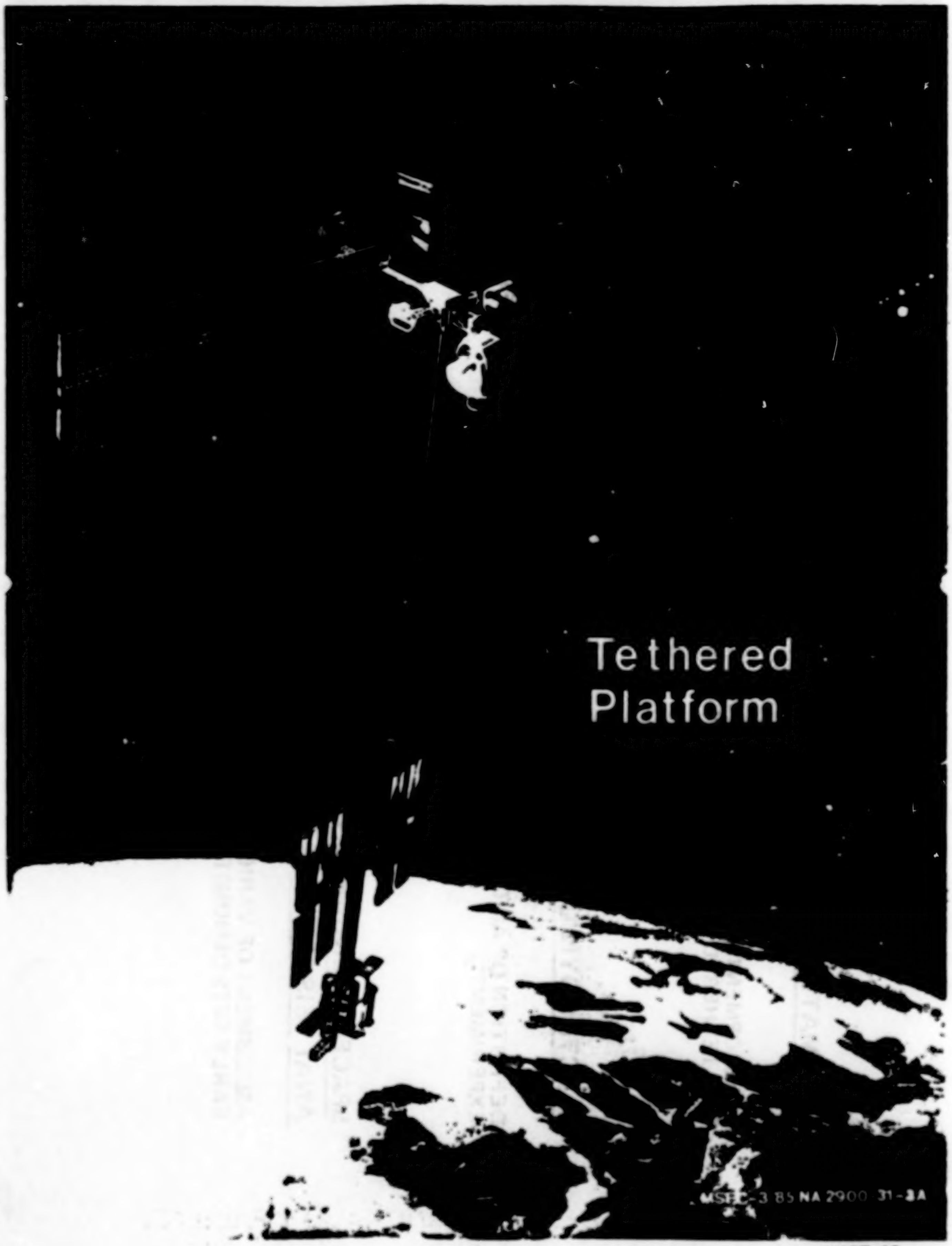

Tethered Platform

MSFC-3-85 NA 2900-31-3A

CHART 18

AUTOMATED GUIDANCE FOR TETHER MEDIATED RENDEZVOUS STUDY

DEVELOPMENT OF AN ALGORYTHM FOR REMOTED DOCKING OF AN ORBITER TO A TETHERED DOCKING FACILITY OF THE SPACE STATION

ELECTRODYNAMIC ULF/ELF ANTENNA SYSTEM

DEFINITION OF AN OVERALL ULF/ELF COMMUNICATION SYSTEM AND PRECURSOR FLIGHT EXPERIMENT

SPACE EXPENDABLE TETHER SYSTEM (SETS) PAYLOAD MISSION ANALYSIS STUDY

ASSESSMENT OF VARIOUS AVAILABLE INSTRUMENT CARRIERS AS PAYLOADS FOR EARLY SETS DEMONSTRATIONS

CHART 19

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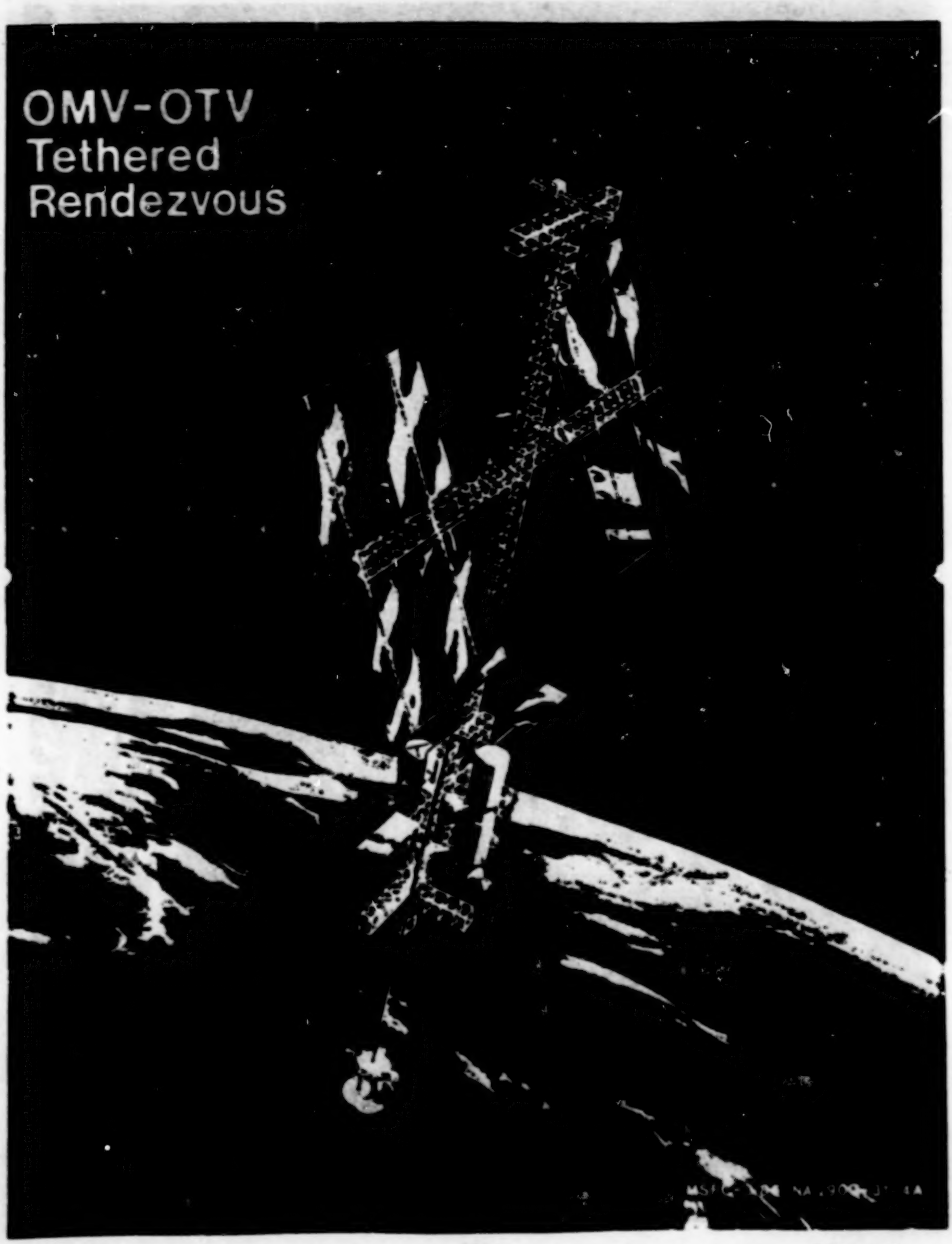
OMV-OTV
Tethered
Rendezvous

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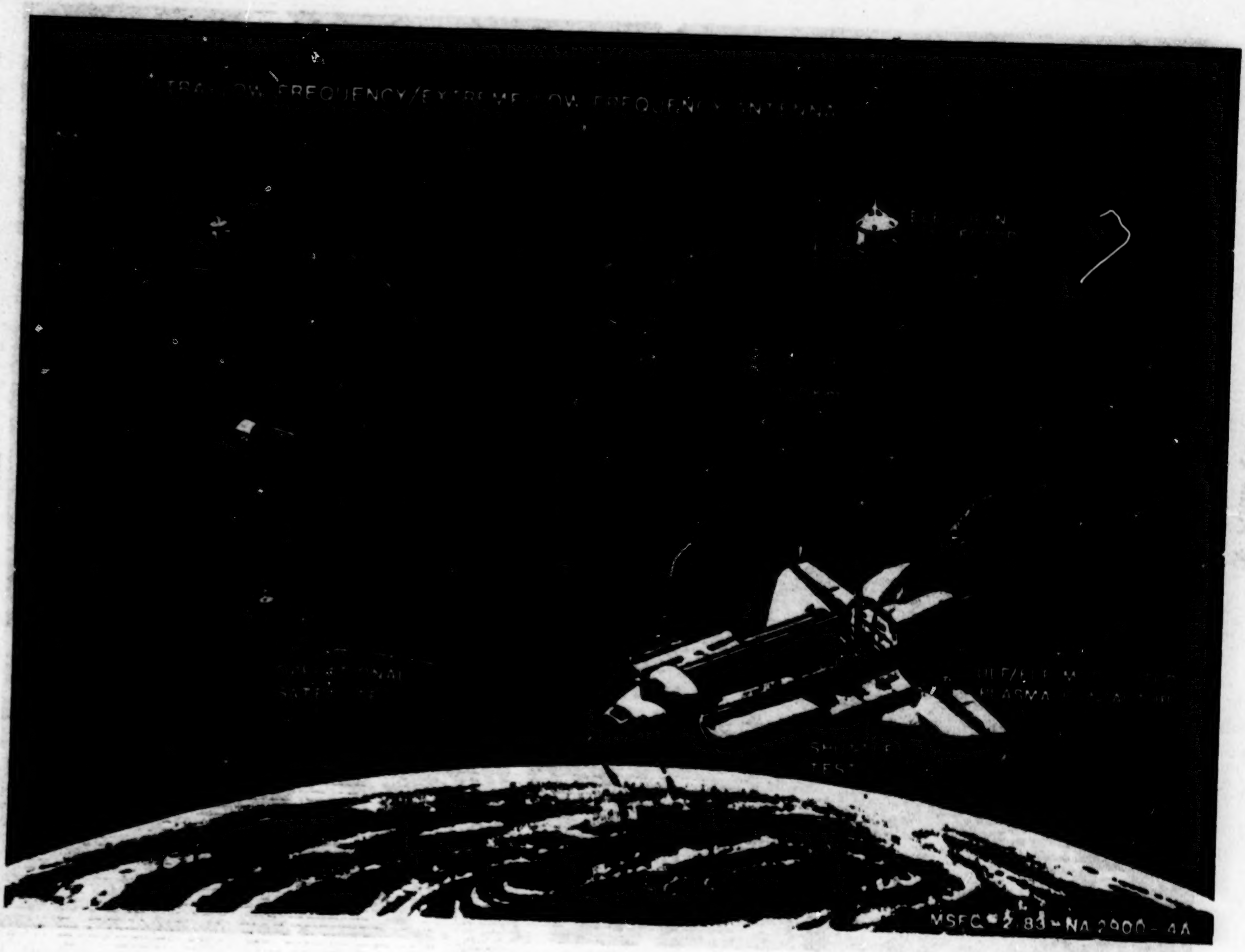
ULTRA LOW FREQUENCY/EXTREMELY LOW FREQUENCY ANTENNA
PLASMA
MSFC-2-83-NA 2900-4A

CHART 21

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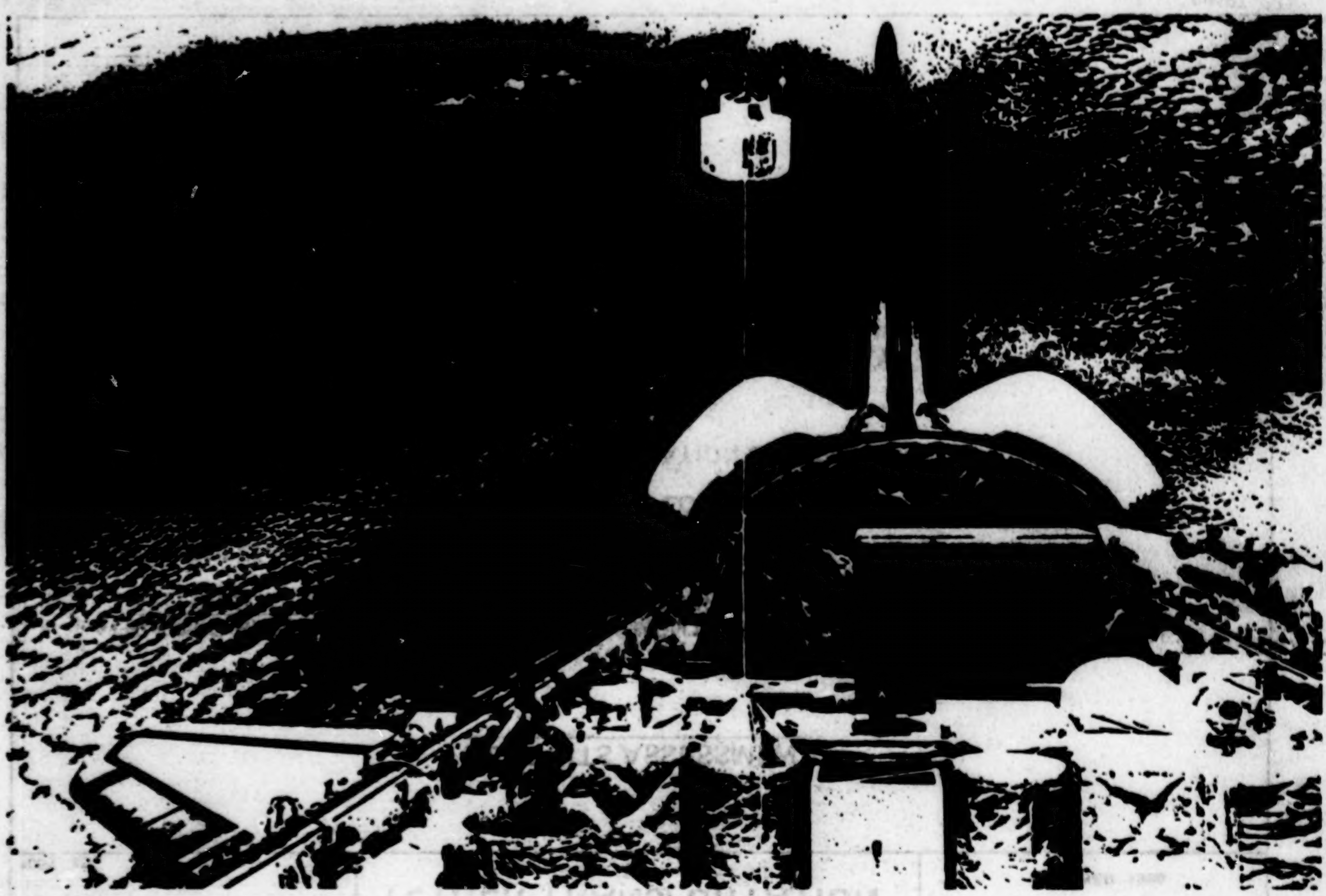

CHART 22

ORGANIZATION: PROGRAM DEVELOPMENT	MARSHALL SPACE FLIGHT CENTER	NAME: GEORG von TIESENHAUSEN
CHART NO.: 4651-85	TETHER TRANSPORTATION	DATE: OCTOBER 1985

BENEFITS ASSESSMENT

- ORBITER BASED PAYLOAD MASS DEPLOYMENT < ~ 12,000kg LIMITED WHEN TETHER DEPLOYER MASS APPROACHES ORBITER OMS PROPELLANT SAVINGS

  NET PROPELLANT SAVINGS < 7500 kg

- SPACE STATION BASED PAYLOAD MASS DEPLOYMENT < 100 TONNES (ORBITER)

  PROPELLANT SAVINGS: OMS, OMV, OTV, STATION DRAG MAKE–UP

  NET PROPELLANT SAVINGS:

1991–1994	< 9,000kg ANNUALLY
1995–2000	< 50,000kg ANNUALLY

CHART 23

ORGANIZATION: PROGRAM DEVELOPMENT	MARSHALL SPACE FLIGHT CENTER	NAME: GEORG von TIESENHAUSEN
CHART NO.: 4650–85	TETHER TRANSPORTATION	DATE: OCTOBER 1985

SHUTTLE EXPENDABLE TETHER SYSTEM:

- PRESENTLY UNDER DEVELOPMENT
- PRIME CANDIDATE FOR PAYLOAD DEPLOYMENT DEMONSTRATIONS
- LOW TETHER TENSION DEPLOYMENT. SWING THROUGH LOCAL VERTICAL AND RELEASE AT BOTH TETHER ENDS.
- PROPOSED FLIGHT EXPERIMENT FOR FY87
- POTENTIAL PAYLOADS
  - RECOVERABLE REENTRY CAPSULE
  - UPWARD DEPLOYMENT OF A PDP, SPARTAN, XSAT, AND OTHER AVAILABLE INSTRUMENT CARRIERS

ORGANIZATION: PROGRAM DEVELOPMENT	MARSHALL SPACE FLIGHT CENTER	NAME: GEORG von TIESENHAUSEN
CHART NO.: 4652–85	**TETHER TRANSPORTATION**	DATE: OCTOBER 1985

NECESSARY CONDITIONS TO ACHIEVE ORBITER MISSION BENEFITS

- LIGHT WEIGHT DEPLOYMENT SYSTEM WITH MINIMUM VOLUME
- DISPOSABLE TETHER PAYLOAD DEPLOYMENT

  UNDER CERTAIN CONDITIONS PAYLOAD RETRIEVAL ADVANTAGEOUS BY ORBITER RENDEZVOUS
- PAYLOAD UPWARD DEPLOYMENT TOWARD END OF ORBITER MISSION
- HAVING ONE PAYLOAD AMONG SEVERAL THAT REQUIRES A HIGHER ALTITUDE
- MAXIMUM PAYLOAD MASS DEPLOYED UPWARD ~ 12,000kg FROM NOMINAL ORBITER ALTITUDE (300km)

ORGANIZATION: PROGRAM DEVELOPMENT	MARSHALL SPACE FLIGHT CENTER	NAME: GEORG von TIESENHAUSEN
CHART NO.: 4653-85	**TETHER TRANSPORTATION**	DATE: OCTOBER 1985

INSIGHTS GAINED FROM TETHERED TRANSPORTATION STUDIES

TETHER ISSUES

- DESIGN FOR ACCEPTABLE RECOIL
- MULTIPLE REUSE DURABILITY
- DEBRIS COLLISION HAZARD

ENERGY MANAGEMENT

- GENERATED BY DEPLOYMENT ~ 15–20kWh (ORBITER); 20–400 kWh (SPACE STATION)
- REQUIRED FOR RETRIEVAL ~ 1–2 kWh NORMALLY; UP TO 30kWh WITH EXTRA BATTERIES (ORBITER); UP TO 70kWh (SPACE STATION).

ORBITER AND SPACE STATION IMPACTS

- INDUCED ACCELLERATION LEVELS (~ 10^{-4}g)
- ORBIT PERTURBATIONS
- STRUCTURAL STRESS
- DEPLOYER SYSTEM LOCATION REQUIREMENTS AND MASSES
- ENERGY SUPPLY AND DISPOSAL REQUIREMENTS
- BENEFITS TO STATION, ORBITER, OTV AND OTHERS

CHART 26

ORGANIZATION: PROGRAM DEVELOPMENT	MARSHALL SPACE FLIGHT CENTER	NAME GEORG von TIESENHAUSEN
CHART NO.: 4654–85	TETHER TRANSPORTATION	DATE: OCTOBER 1985

OUTLOOK FOR 1986 IN TETHERED TRANSPORTATION

- ENGINEERING ANALYSES AND COST/BENEFIT DETERMINATION OF:
  - ORBITER DEPLOYMENT FROM SPACE STATION } COMBINED
  - OTV LAUNCH FROM SPACE STATION } COMBINED
  - PAYLOAD DEPLOYMENT AND RETRIEVAL FROM ORBITER
  - TETHERED SPACE PLATFORMS
- SPACE EXPENDABLE TETHER SYSTEM DEVELOPMENT
  - EXPECTED FLIGHT READINESS – 1988
- DEMONSTRATION MISSION PAYLOADS DEFINITIONS FOR EXPENDABLE TETHER SYSTEM
- SPECIALIZED TETHER SIMULATION PROGRAM DEVELOPMENT
- TETHER REMOTE DOCKING ANALYSIS (SPACE STATION)
- SPACE STATION TETHERED PLATFORM WITH MOVABLE, VARIABLE G MODULE
- KITE FLIGHT EXPERIMENT DEFINITION
- ULF/ELF ANTENNA SYSTEM

CHART 27

THE FOLLOWING INDUSTRIES, INSTITUTIONS, AND NASA FIELD CENTERS HAVE BEEN PARTICIPATING IN RESEARCH AND DEVELOPMENT OF THESE APPLICATIONS.

INDUSTRIES:

- MARTIN MARIETTA AEROSPACE
- BALL AEROSPACE COMPANY
- McDONNELL DOUGLAS CORPORATION
- BOEING AEROSPACE CORPORATION
- CONTROL DYNAMICS COMPANY
- ENERGY SCIENCE LABORATORIES
- ANALYTICAL MECHANICS ASSOCIATES
- S—CUBE CORPORATION
- MATERIALS CONCEPTS INCORPORATED

INSTITUTIONS:

- SMITHSONIAN ASTROPHYSICAL OBSERVATORY
- UNIVERSITY OF CALIFORNIA – SAN DIEGO
- UNIVERSITY OF UTAH
- UNIVERSITY OF ALABAMA – HUNTSVILLE
- STANFORD UNIVERSITY

NASA FIELD CENTERS:

- MARSHALL SPACE FLIGHT CENTER
- JOHNSON SPACE CENTER
- GODDARD SPACE FLIGHT CENTER
- LANGLEY RESEARCH CENTER
- LEWIS RESEARCH CENTER
- AMES RESEARCH CENTER
- JET PROPULSION LABORATORY

CHART 28

CONTROLLED GRAVITY

Luigi Napolitano
Istituto Aerodinamica U. Nobile

Mr. Napolitano's presentation is summarized in his paper which is reproduced in the Controlled Gravity Panel Presentations, entitled, "Tethered Constellations, Their Utilization as Microgravity Platforms and Relevant Features."

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N86-28417

U.S. GRAVITY UTILIZATION OF TETHERS ACTIVITY

Ken Kroll
Johnson Space Center, NASA

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I'm going to talk about three things: the ongoing study on fluid transfer that Martin-Marietta is doing right now, our future planning, and some of the issues we have in gravity utilization.

The first thing you need to know about tether orbital refueling is that it's for basically one reason: to settle fluid, overcome the surface tension forces that we see in space with the gravity level (see Figure 1). This allows us to have an earth-like environment where the liquid is over an outlet and the gas is over a vent so that we can perform as normal.

It also allows us to have a separation, when we are on the Space Station, from contamination and also from explosion hazards, though that's not as great a hazard as the contamination.

The important thing here for the acceleration to overcome the surface tension is its dependence upon the fluid properties, the acceleration level and the tank diameter, which is defined by the bond number.

And, if you look at Figure 2, which shows the acceleration in tether length versus different propellants, which is what we are looking at here, you will notice that there is quite a difference. It is very sensitive to tank diameter. The cryogenic propellant tank diameters are fairly large because of the large propellant quantities, and it's very good for settling with a tether gravity. Because both the use of this propellant and the opportunity to use a tethered depot will come later than an IOC Space Station, and also because of the technical reason that it settles well, we are concentrating on the cryogenic propellants for settling with the tether.

Once we settle the propellants, the most important thing is the fluid slosh (Figure 3). We can't cover the vent or uncover the propellant outlet. And, for a single disturbance, we can increase the tether length in order to increase potential energy of any slosh motion and we can change tank shape. Typically, we will have a conical bottom to provide the best tank shape. Now, for multiple disturbances, we have to damp this slosh motion. Typically, we would use a ring-type baffle to do that.

It turns out that the major impact, or the major issue, on the tether for a propellant depot is going to be the impact on the Space Station (Figure 4). The actual settling of the propellant and the slosh control are fairly easily done.

Going on to planning, we see that in the coming two years we are planning on doing a gravity laboratory study (Figure 5). Here, I define micro-gravity as trying to get the minimum disturbance level, and low gravity as purposely providing a gravity level, just to get the nomenclature across. We are looking at both types of laboratories, and also want to look at the low gravity processes to try and identify some so that we can understand what type of laboratory we do need, and the type of technology we would like to look at. Gravity level instrumentation is on top of the list. The crawler mechanism is a means of going from one end of the tether to the other. We would like to look at this both for logistics reasons, and also for an experiment using different gravity levels. Also very important is the disturbance-damping tether. Disturbances are damped very well laterally, but actually it is much more uncertain. We would like to look at the different tether weaves and combinations to see if we can dampen disturbances in the axial direction.

Currently we are planning a demonstration of gravity utilization using a TSS type of deployer (Figure 7). I am currently thinking of having the end satellite perform a fluid transfer to demonstrate a low-g application, and then having a crawler on the tether itself, moving around trying to position itself with the CG and performing gravity measurements as it goes along the tether.

And, as for a low gravity laboratory itself (Figure 8), my thinking is currently that a TSS-type of device on the Space Station itself would be best because it allows a long-term experiment and reduces the number of times that we have to bring up the deployer.

Getting into issues (Figure 9), the first thing in this particular area is the fact that we can't trade capital costs for operating costs. We are going to have to look at how much it's going to cost us extra, period, to have the tether. And the benefits that we get out of it, in terms of gravity utilization, will have to make that worthwhile.

The second point is the fact that we are going to be impacting the Space Station itself, especially for permanently deployed platforms like a transfer depot. This would be in terms of induced gravity, which would move the zero gravity point off the Space Station if it was the only platform. And also operational complexities, especially in terms of proximity operations. How do you supply those platforms? And how do you dock to the Space Station? And things like that.

Another point is, some of the platforms may want to be temporarily deployed, and some permanently. As we get more tether platforms up there, we are going to be wanting—providing—more permanent deployent. But, initially, we should be able to get away with some temporary ones.

Should we be remotely or manually controlling experiments or operations on the platform itself? This is important in terms of how much the astronaut has to EVA, if it's manual. If it's not, we have to try some remote method to keep the cost down, and keep the experiment as simple as possible. Another important point is that a Space Station doesn't appear to lend itself to medical experiments. Because with medical experiments, we have to start spinning the tether. How do we implement this in terms of a total Space Station that will be having a spinning tether as a free-fly or whatever?

And the last point. If we are going to have a lot of tether applications utilized simultaneously, I'd like to make the point that we could probably save some money if we integrate the tether systems together. This is to allow for more competitiveness with its conventional alternatives, since all these concepts do have conventional alternatives. It will allow us to share the cost of the tether control systems, and the cost of the additional hardware and operational development that we have to have with a permanently deployed tether.

Another important thing is micro-gravity. Because as I said before, if we have a tethered platform on a Space Station, it's going to move the micro-gravity point off of the station. We may want to do the micro-gravity still on the Space Station, because the modules will already be there. So we might have to balance different tether applications, one on each side of the Space Station. Or, we just might want to move everything to the micro-gravity laboratory on the tether itself. It also allows us to simultaneously use multiple tether applications. If we don't have an integrated concept, we can only use one at a time. In fact, some of these applications can complement each other, especially the electrodynamic tether. It can provide power into the platforms and whatever.

That completes my presentation.

U.S. GRAVITY UTILIZATION OF TETHERS ACTIVITY

KEN KROLL

NASA, JOHNSON SPACE CENTER

OCTOBER 15, 1985

TETHERED ORBITAL REFUELING STUDY

OBJECTIVE

0 EVALUATE FEASIBILITY, REQUIREMENTS, AND LIMITATIONS OF FLUID TRANSFER ON A TETHERED SYSTEM

PURPOSE

0 SIMPLIFY FLUID TRANSFER
  0 TETHER ACCELERATION SEPARATES FLUID PHASES
  0 LIQUID OVER OUTLET
    0 LIQUID ACQUISITION IN RECEIVER TANK
  0 GAS OVER VENT
    0 VENT PRESSURE IN RECEIVER TANK
    0 REDUCE CONTAMINATION BY VENTING GAS TO SUPPLY TANK

0 IMPROVE SAFETY
  0 TETHER LENGTH SEPARATES HAZARDS FROM SENSITIVE AREAS
  0 PROPELLANT CONTAMINATION REDUCED
    0 LEAK OR VENT HIGHLY LIKELY
  0 EXPLOSION HAZARD REDUCED
    0 OVERPRESSURE OR DETONATION HIGHLY UNLIKELY
  0 TETHER BREAKAGE IS NEW HAZARD
    0 DEBRIS IMPACT OR TETHER DEGRADATION MODERATELY LIKELY

NASA-S-84-05269

Fluid Settling

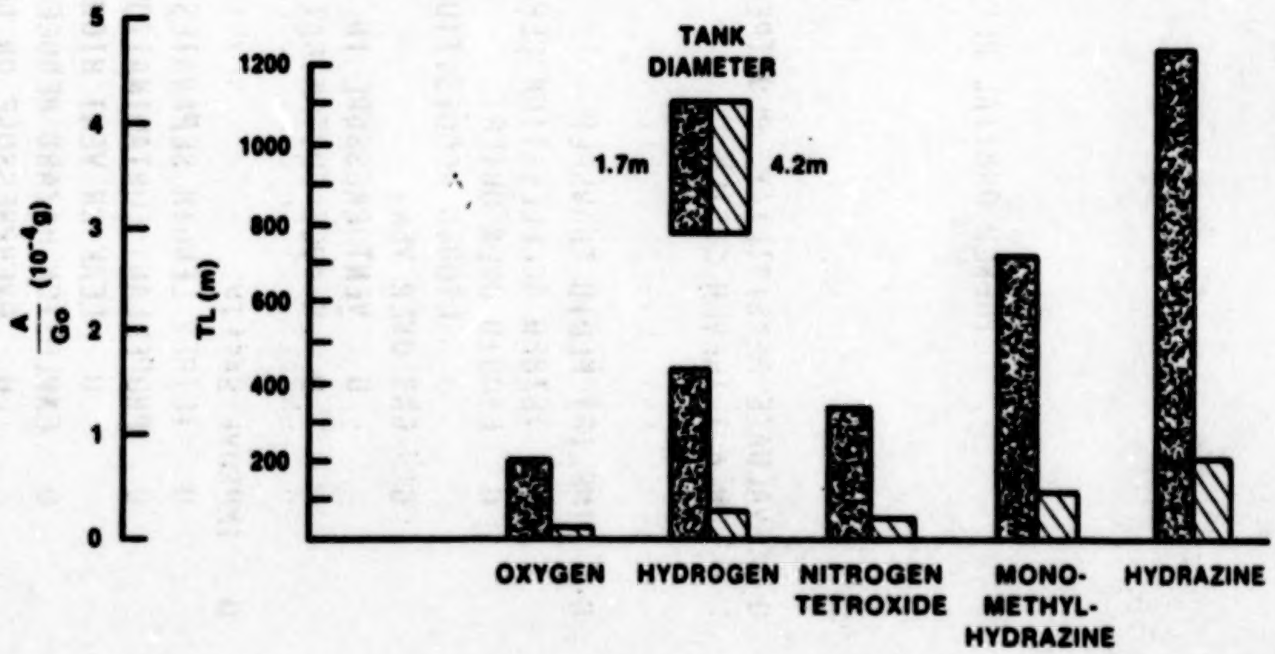
- **SETTLING REQUIREMENT**
  - **GRAVITY DOMINATE SURFACE TENSION**
- **FLUID SETTLING PARAMETER IS BOND NUMBER (Bo)**

$$Bo = \frac{\rho^{*}A^{*}D^{2}}{4^{*}\sigma}$$

ρ = FLUID DENSITY
σ = SURFACE TENSION COEFFICIENT
D = TANK DIAMETER

- **FLUID SETTLES IF Bo > 10**
  - **Bo = 50 CHOSEN TO BE CONSERVATIVE**

PROPELLANT SETTLING ON A STATIC TETHER (Bo = 50)



FLUID TRANSFER

- O TRANSFER METHODS
  - O CRYOGENIC PROPELLANTS - AUTOGENOUS PRESSURIZED TRANSFER
  - O STORABLE PROPELLANTS - PUMPED TRANSFER
  - O BACKUP - GRAVITY FEED TRANSFER
- O FLUID SLOSH
  - O SLOSH CAN UNCOVER OUTLET AND COVER VENTS
  - O LARGEST DISTURBANCE IMPULSE IS DOCKING WITH SPACE SHUTTLE
  - O LIQUID POTENTIAL ENERGY CAN ABSORB DISTURBANCE ENERGY
    - O TETHER LENGTH - 1 Km
    - O TANK SHAPE - CONICAL BOTTOM
    - O SINGLE DISTURBANCE
  - O INTERNAL BAFFLES DAMP ENERGY
    - O MULTIPLE DISTURBANCES
    - O LITTLE CHANGE TO INITIAL AMPLITUDE

SPACE STATION IMPACTS

- REFUELING FACILITY PERMANENTLY DEPLOYED
  - CONTAMINATION CONCERNS
  - LARGE DEPLOYMENT MASS
  - CROWDING OF SPACE STATION PROPER
- LARGE SHIFT IN CENTER OF GRAVITY
  - ACCELERATION ON MICROGRAVITY LABORATORY
  - PLACE MICROGRAVITY LABORATORY ON TETHER
  - COUNTERBALANCE WITH ANOTHER TETHER APPLICATION
- PROPULSIVE FERRYING OPERATIONS WILL BE COMPLICATED
  - FERRY VEHICLES, MATERIALS, AND MEN
  - PROPULSIVE FERRYING WILL REQUIRE ORBITAL TRANSFER MANEUVERS
  - PROPULSIVE FERRYING WILL REQUIRE FAST DOCKING
  - FERRYING ALONG TETHER (CRAWLER) PROBABLY PREFERABLE
- REMOTE RATHER THAN MANUAL CONTROL OF OPERATION
  - REMOTE LOCATION
  - ACCELERATION ON EVA PERSONNEL

PLANNING RECOMMENDATIONS
GRAVITY LABORATORY STUDY

- FISCAL YEAR 1986
  - MICROGRAVITY LABORATORY
    - DETERMINE REQUIREMENTS AND LIMITATIONS
      - SPACE STATION AT CENTER OF GRAVITY
      - LABORATORY CRAWLER AT CENTER OF GRAVITY
    - DETERMINE COST AND BENEFITS
  - LOW GRAVITY PROCESSES
    - DETERMINE CANDIDATE PROCESSES FOR RESEARCH
    - DETERMINE CANDIDATE PROCESSES TO INVESTIGATE MICROGRAVITY BOUNDARY
    - DETERMINE CANDIDATE PROCESSES FOR INDUSTRIAL USE
- FISCAL YEAR 1987
  - LOW GRAVITY LABORATORY
    - DETERMINE REQUIREMENTS AND LIMITATIONS
      - LABORATORY AT TETHER END
      - LABORATORY CRAWLER
    - DETERMINE COST AND BENEFITS

PLANNING RECOMMENDATIONS
TECHNOLOGY

- FISCAL 1987 TO 1989

- GRAVITY LEVEL INSTRUMENTATION
    - DETECT DISTURBANCE LEVELS
    - CONTROL POSITION RELATIVE TO THE CENTER OF GRAVITY

- CRAWLER MECHANISM
    - PROVIDE MICROGRAVITY LABORATORY POSITIONING
    - PROVIDE LOW GRAVITY LABORATORY POSITIONING
    - PROVIDE FERRY CAPABILITY ALONG TETHER

- DISTURBANCE DAMPING TETHER
    - REDUCE EFFECT OF AXIAL TETHER DISTURBANCES

PLANNING RECOMMENDATIONS
DEMONSTRATION

- 0 FY87 - DEMONSTRATION DEFINITION
- 0 FY88 - 91 - DEMONSTRATION DEVELOPMENT
- 0 FY92 - DEMONSTRATION FLIGHT

- 0 DEMONSTRATION ELEMENTS
  - 0 TSS DEPLOYER
  - 0 FLUID TRANSFER EXPERIMENT ON END SATELLITE
    - 0 DEMONSTRATE FLUID TRANSFER
    - 0 VERIFY FLUID AND SYSTEM DYNAMICS
    - 0 TETHER LENGTH FROM CENTER OF GRAVITY GREATER THAN 8 KM
  - 0 CRAWLER
    - 0 DEMONSTRATE CRAWLER
    - 0 VERIFY CRAWLER DYNAMICS
    - 0 VERIFY PLACEMENT ACCURACY AT CENTER OF GRAVITY
    - 0 DETERMINE DISTURBANCE LEVEL AT CENTER OF GRAVITY

PLANNING RECOMMENDTIONS
LOW GRAVITY LABORATORY

- FY88 - DEFINITION STUDY

- LOW GRAVITY LABORATORY ELEMENTS
  - SPACE STATION BASED
    - LONG TERM EXPERIMENTS
    - SINGLE SHUTTLE FLIGHT
    - MULTIPLE EXPERIMENTS
  - BASED ON TSS
    - USE ON IOC SPACE STTION
    - DEPLOYABLE TO MINIMIZE SPACE STATION IMPACT
  - PROCESS EXPERIMENTATION ONLY

ISSUES

- IS A TETHER WORTH THE EXTRA COST?
- HOW IS IMPACT TO SPACE STATION TO BE HANDLED?
  - INDUCED GRAVITY
  - OPERATIONAL COMPLEXITY
- SHOULD PLATFORMS BE TEMPORARILY OR PERMANENTLY DEPLOYED?
- SHOULD EXPERIMENT AND OPERATIONS ON PLATFORMS BE REMOTELY OR MANUALLY CONTROLLED?
- HOW SHOULD GRAVITY LEVEL MEDICAL EXPERIMENTS BE CONDUCTED IN A SPACE STATION SYSTEM?

CASE FOR AN INTEGRATED TETHERED SPACE STATION

- O INTEGRATED TETHER SYSTEM CAN SHARE COSTS
  - O ALL TETHER APPLICTIONS HAVE MORE CONVENTIONAL ALTERNATIVES
  - O COST FOR TETHER AND CONTROL SYSTEM
  - O HARDWARE AND OPERATIONS COSTS OF PERMANENTLY DEPLOYED TETHER

- O PROVIDE MICROGRAVITY LABORATORY REQUIREMENT WITH PERMANENTLY DEPLOYED TETHER
  - O BALANCED TETHER APPLICATIONS
  - O MICROGRAVITY LABORATORY ON TETHER

- O SIMULTANEOUS USE OF MULTIPLE TETHER APPLICATIONS
- O TETHER APPLICATIONS CAN COMPLEMENT EACH OTHER

N86-28418

TETHER APPLICATIONS FOR SPACE STATION

William Nobles
Martin Marietta

What I will be discussing with you this afternoon are a subset of the results from a study performed by Martin-Marietta Aerospace for Marshall Space Flight Center under the technical guidance of Georg von Tiesenhausen and Jim Harrison. During his earlier talk, Georg has already touched on some of the subjects that I will be talking about this afternoon.

We have looked at a wide variety of Space Station applications for tethers. Many of those will affect the operation of the Station itself while others are in the category of research or scientific platforms. My co-speaker will focus on the latter of these. I would like to discuss what we believe is one of the most promising potential applications that could increase the overall efficiency of the Space Transportation System in supporting the Space Station.

One of the most expensive aspects of operating the Space Station will be the continuing Shuttle traffic to transport logistic supplies and payloads to the Space Station. We must pay the freight bill for getting the Orbiter and its payload up into orbit, and then we pay the bill again when it comes back. If we can find a means to use tethers to improve the efficiency of that transport operation, it will increase the operating efficiency of the system and reduce the overall costs of the Space Station. The concept we have studied consists of using a tether to lower the Shuttle from the Space Station. This results in a transfer of angular momentum and energy from the orbiter to the Space Station. Our study has delved into the consequences of this transfer and how beneficial use can be made of it.

Please keep in mind that, if we have scavenged angular momentum from the tether de-orbiting of the Shuttle, we must then be able to beneficially use that angular momentum. I'd like to change the old saying "You can't have your cake and eat it, too" to a little different version - "Unless you can eat your cake, you really haven't had it." The point here is that, if we do not have a beneficial way to use this angular momentum we have scavenged, we will quicky choke on it, because the altitude of the Space Station has been boosted up to where it becomes impractical for the follow-on missions to reach it.

In our study we have considered two alternative ways of accomplishing this required angular momentum balance. On my first slide (Figure 4) please direct your attention to the left side of the screen. Here I have shown one of our alternative approaches. Note the balance beam at the bottom to indicate we are balancing the Shuttle tether de-orbit against a tether launch assist for an orbital transfer vehicle. I'll show you in a few moments how we propose to implement that.

To review the concept here--let's start at the point where the STS comes up to rendezvous with the station. It operates in conjunction with the station for some period of time, and then does a tether-assisted de-orbit. At this point, there is a very significant increase in the altitude of the station. This is due to the angular momentum transfered to the Space Station from the Orbiter by the tether. We have used the altitude bounds of 250 nautical miles, which is a practical lower operating unit for the Space Station, and an upper limit of 310 nautical miles.

You can see that the Shuttle tether de-orbit gives a boost of a significant fraction of that range. It must then be followed in fairly close order with a corresponding tethered launch assist of the orbital transfer vehicle in an upward direction which, in turn, will drop the altitude of the station back down to a more reasonable operating range in preparation for the next Shuttle rendezvous mission.

For this process to continue, the downward and upward tether assisted launches must alternate in coordinated pairs to keep the angular momentum of the Space Station in balance.

Now, in contrast, look at the righthand side of the slide where the Shuttle de-orbit is balanced against an electrodynamic tether for power generation. Here there is a significantly more flexible capability to achieve balance. What I have indicated here is a system where the angular momentum and energy scavenged from the Shuttle by the tether de-orbit is subsequently converted into electrical power by means of an electrodynamic tether power system.

The concept design is sized to operate at 25 kilowatts of power with the reserve capability of going up to 75 kilowatts. An interesting feature of this type of system is that they can be operated at a higher power level with the only penalty some loss of efficiency in converting the orbital mechanical energy into electrical power.

As a point of reference, if you operate the power tether at a 25-kilowatt conversion rate, you can maintain full duty cycle operation for approximately one month on the mechanical energy derived from one Shuttle de-orbit.

At the other extreme, if you want to lower the Space Station more rapidly and, presuming there is a way to use the power produced, a 75 kW conversion rate will return the Space Station to its original altitude in about a week. I'll discuss this in more detail a little later.

To reiterate, this second momentum balance concept is much more controllable in that the rate of converting the angular momentum can be regulated and, if there is a need to be back down to a lower altitude by a certain time, it can be done. To illustrate our approach to implementing these concepts, my next slide (Figure 6) shows a line drawing of the same concept that Georg had shown you earlier in a more colorful artist's rendition. I want to point out the dual mode tether reel assembly that can perform both the Shuttle de-orbit and the OTV launch assist. It is centrally located on the Space Station and incorporates the tether tension alignment systems at both the upper and the lower ends of the Space Station.

Here on the next slide (Figure 9) you see the Shuttle attached at the lower end. In this scenario, the Shuttle would have delivered an orbital transfer vehicle payload intended for a subsequent delivery mission to geosynchronous orbit. That OTV payload has been transferred up to the assembly area on the upper end of the Space Station. The next step is for the Orbiter to separate from the station. It is then deployed downward on the tether to a length of 65 kilometers.

One of the interesting aspects of this de-orbit process is that the amount of propellant that is required for the Orbiter to re-enter is significantly reduced.

For a time, we were stymied as to how to take advantage of this. It can't be offloaded from the Orbiter until after you are down at that tether release altitude because, if the tether operation went awry somehow, the Orbiter would be stranded, and would have to come back to the station for propellant resupply before completing the re-entry.

As a solution we developed a concept to incorporate propellant scavenging tanks into the tether attach fixture that interfaces with the Orbiter. Now, as you lower the Orbiter down on the tether, these tanks are connected with the propellant storage system of the Orbiter. As the Orbiter is lowered and the propellant becomes excess to need, it is transferred from the Orbiter into the tether system scavenge tanks. At the full 65 km length, 6500 pounds of propellant will have been transferred. After separation, this scavenged propellant is retrieved by the tether. I will elaborate more later on how that adds up as savings.

Shown here on the next slide (Figure 10) is the other operation at the upper end of the station. Subsequent to the Shuttle de-orbit, a similar tether deployment of the OTV stack is performed from the upper end of the Space Station using the same tether deployment system. We examined the design requirements for commonality for the Orbiter and OTV deployments, and found that, if the orbital transfer vehicle were deployed out to a tether length of 150 kilometers, it would develop equivalent tensions in the tether to those resulting from the Orbiter at

65 km. This means we could use a common design for the tether and the deployer reel drive system. The OTV launch assist does require more storage of tether on the reel. It looks feasible to design one system that can perform both of these deployment operations.

My next slide (Figure 12) is similar to one shown earlier by Georg. It shows the benefits that accrue over a decade of operations. This analysis is based on Space Station mission model revision 7. The vertical scale is in terms of reduced requirements to transport propellant to the Space Station.

I first direct your attention to the lowest set of bars coded with a double crosshatch. This represents the Space Station saving in drag makeup propellant. This orbit maintenance function is accomplished by the Shuttle de-orbit operations, therefore, this stationkeeping propellant is no longer required. Note the change as we go into the later years of the decade. This is due to the reduced atmospheric drag during the quiet years of the solar cycle. The early years of the Space Station will be the ones with the most demand for drag makeup propellant.

The next element of transport saving is represented by the single crosshatch which stands for the propellant scavenged from the Shuttle. This is plotted at the upper end of the vertical bars. This shows the amount of propellant that we have scavenged from the Shuttle and retrieved for use in spacecraft such as the orbital maneuvering vehicle.

Note that the benefit here is very limited during the early years of the decade. This limit holds until the space-based orbital transfer vehicle comes into operation in 1995.

Until that time, the amount of Shuttle tether de-orbits that can be utilized is that corresponding to the relatively small amount required for Space Station drag makeup. Here again I want to emphasize that you must have a way to beneficially utilize the scavenged angular momentum before you can take full advantage of the process. Notice that out here in the later years, when the orbital transfer vehicle comes into full operation, that we have these much more significant amounts of OMS propellant because we can now use a full length tether de-orbit on more of the Shuttle missions.

A third major element of benefit is the reduced amount of cryogenic propellant for the OTV missions. This is coded as the clear portion of the bars. This reduction is due to the launch assist given the OTV by the tether system.

So we have these three major elements of propellant transport saving. The propellant that is no longer required at the Space Station to do the drag makeup, the reduced amount of cryogenic propellant for the orbital transfer vehicle, and the Orbiter propellant that is scavenged during the Shuttle de-orbit.

Starting with my next slide (Figure 14), I'd like to take you through a similar kind of benefits analysis for the electrodynamic tether and show you how that case differs. The system design constraints are listed. We used 25 kW as our design requirement for the electrodynamic power tether. It was designed for a system conversion efficiency of 80 percent. In order to achieve this efficiency, no more than 5 percent of the system power could be dissipated in the tether as heating.

If the power level is increased up to 75 kilowatts, this efficiency drops to 70 percent, as I will show you later.

We designed the system so that the tether angle from vertical is always less than one-tenth of a radian, or about six degrees, even when operated at the 75 kW reserve power level. The reason we did this is to prevent the electrodynamic drag on the power tether from tilting the station when it's drawing maximum power. We wanted to keep that angle small enough so that one of our tension alignment stages could be used to keep the station vertical.

The assumptions used for the Space Station itself are a mass of 250,000 kilograms in a 500-kilometer orbit. It now looks as if the station will grow to a larger mass than that in the more mature phases. That will tend to further improve the overall arithmetic on this system.

We have used an end mass of 500 kilograms to support the required subsystems at the end of the tether.

On my next slide (Figure 16) is shown a plot of the relationship between the mechanical energy derived from a tether de-orbit of a Shuttle and the conversion of this energy into electrical power by an electrodynamic power tether. A tether de-orbit of Shuttle causes an 80 km boost in altitude for the Space Station.

On the vertical axis is shown the kilowatt hours per kilometer of orbit altitude. And, as you can see, over this range, it ranges from about 297 kilowatt hours per kilometer of altitude down to about 288. Although stated in electrical units, this is actually mechanical energy content of the orbiting Space Station. If you boost the orbit altitude of the Space Station by 80 km, that results in 21,700 kilowatt hours of mechanical energy that have been transferred into the orbit. I submit to you - that's a rather impressive amount of energy.

Now referring to the table in the upper right of the slide, we can see what happens when we convert that mechanical energy back into electrical power. Note the two columns on the right under the two power levels of 25 kW and 75 kW. The next numbers down give the corresponding system efficiencies in converting that mechanical energy into electrical energy. As I stated earlier, the efficiency is 80 percent at 25 kW and 70 percent at 75 kW. Next you see the number for the orbit altitude loss per day. The bottom entries show that at the 25-kilowatt power level, the system can sustain operations for 29 days and for 8.4 days at 75 kilowatts.

The next slide (Figure 17) is an accrued benefits plot similar to the one shown earlier. The corresponding values look a little bit different here and requires some additional explanation. Again, I have shown the scavenged Orbiter propellant savings. Unfortunately, I changed the marking code and here the Orbiter propellant is shown as the clear bar, and the cross-hatched one is the drag makeup propellant saved. These are the elements making up the bars that are on the left.

Note the significantly increased transport benefits during the early years of Space Station operation. This is because with this concept there is not a requirement to pair a Shuttle de-orbit with an OTV launch assist. The maximum amount of Shuttle propellant can be scavenged from the beginning of Space Station operations.

But now we have this new commodity that came into being with this concept, and that is the amount of electrical power made available on the Space Station. I used the evaluation of a hundred dollars per kilowatt hour on orbit. The accrued numbers of kilowatt hours of electrical energy per year are identified in the shaded bars on the right. The dollar value numbers are at that hundred dollars per kilowatt hour.

The point of this plot, in contrast to the earlier one, is that it does not have the step change due to the advent of the space-based OTV in 1995. It means, if we had an electrodynamic power tether, we could start beneficially utilizing the full available amount of scavenged angular momentum right from the beginning. We could begin as soon as the Space Station is in operation with the capability to sustain such a tether system.

The conclusions that I had made were very close to the ones that Georg had listed. In order to keep on schedule I will skip that slide. My presentation had originally been planned for a longer time so there are some additional slides in the package which I have left there for information.

Thank you for your attention.

TETHER APPLICATIONS
FOR
SPACE STATION

APPLICATIONS OF TETHERS IN SPACE WORKSHOP

VENICE, ITALY

OCT 15-17, 1985

WILLIAM NOBLES

MARTIN MARIETTA

PHASE I STUDY RECAP

- o STUDY COMPLETED JULY 84
- o INITIAL SURVEY OF 26 + CONCEPTS
- o CONCEPTS SELECTED FOR STUDY

CONCEPTS	TETHER LOCATION
A - TETHER DEORBIT OF SHUTTLE	SPACE STATION
C - TETHERED PLATFORM	SPACE STATION
D - TETHER MEDIATED RENDEZVOUS (OMV WITH OTV)	SPACE STATION
E - ELECTRODYNAMIC TETHER (DUAL MODE FOR ENERGY STORAGE	SPACE STATION

INSIGHTS GAINED - CONCEPT REVISIONS MADE

ANGULAR MOMENTUM BALANCE

- THE IMPRESSIVE AMOUNTS OF ANGULAR MOMENTUM MADE AVAILABLE BY TETHER DEORBIT OF SHUTTLE REQUIRES CORRELATED CONCEPTS TO USE IT BENEFICIALLY

REVISIONS

- CONCEPT F - TETHER LAUNCH ASSIST TO OTV MISSIONS
- CONCEPT E2- ELECTRODYNAMIC TETHER AUXILIARY POWER SYSTEM

OMS PROPELLANT SCAVENGING

- AMOUNT OF SURPLUS OMS PROPELLANT (6500 LBS) RESULTING FROM TETHER DEORBIT OF SHUTTLE
- OPERATIONAL SAFETY CONSTRAINTS ON OMS OFF-LOAD PRIOR TO TETHER DEORBIT

REVISION

- CONCEPT A2- TETHER DEORBIT OF SHUTTLE WITH OMS SCAVENGING

FUNCTIONAL PAIRING OF CONCEPTS

- ANGULAR MOMENTUM BALANCE PAIRING OF CORRELATED CONCEPTS
- COMMONALITY OF REQUIREMENTS (A2 AND F)

REVISION

- DUAL MODE DEPLOYER SYSTEM (SHUTTLE DEORBIT, OTV LAUNCH)

PHASE II STUDY CONCEPTS BASELINE

SPACE STATION BASED TETHER

A2 - TETHER DEORBIT OF SHUTTLE WITH OMS PROPELLANT SCAVENGING (REVISION)

F - TETHER LAUNCH ASSIST TO OTV (NEW)

} BASIS FOR DUAL MODE DEPLOYER SYSTEM ON SPACE STATION

C - TETHERED PLATFORM (SAME)

D - TETHER MEDIATED RENDEZVOUS OF OMV WITH OTV (SAME)

E2 - ELECTRODYNAMIC TETHER FOR AUXILIARY POWER SYSTEM (NEW)

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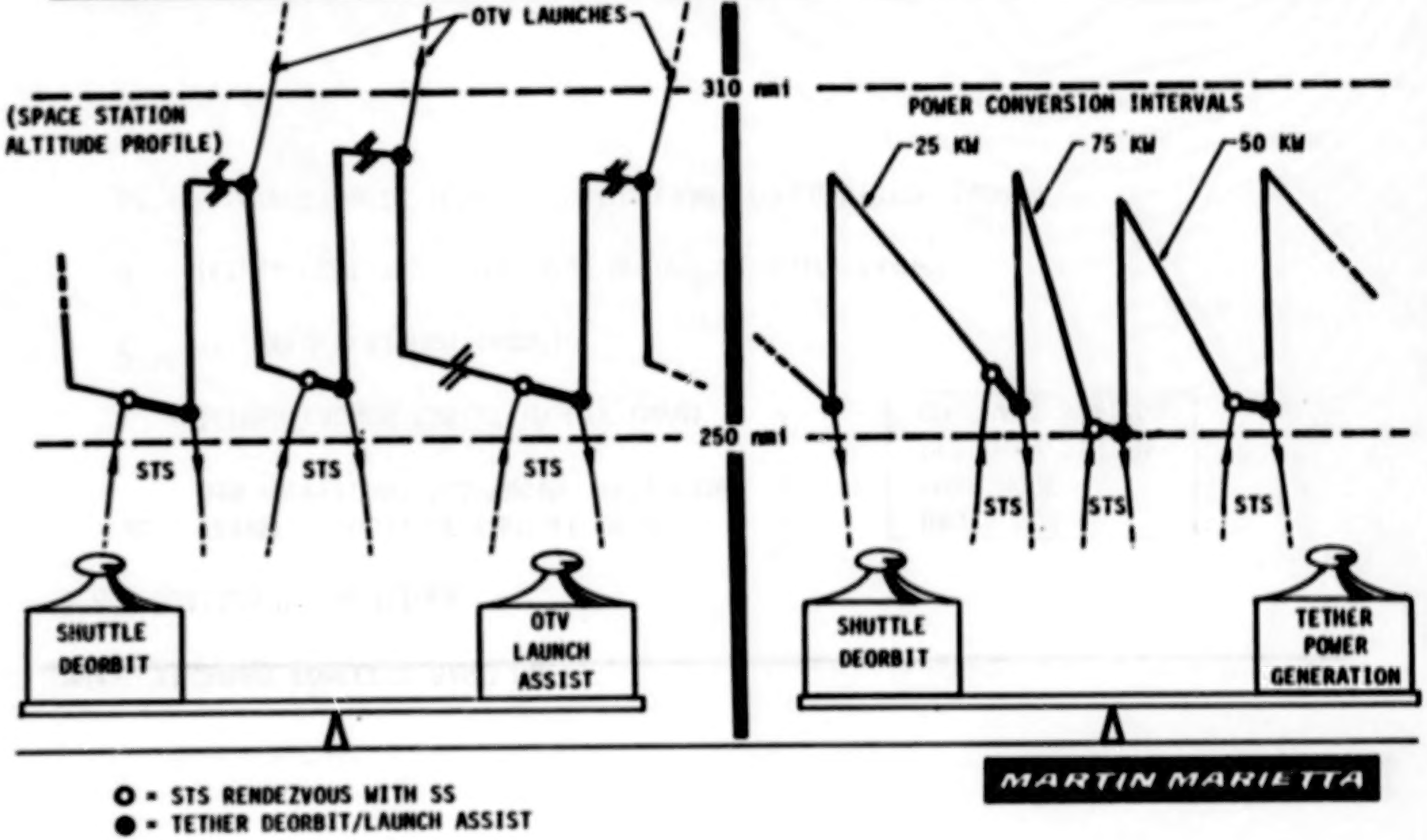
ALTERNATIVE APPROACHES TO ANGULAR MOMENTUM BALANCE


OTV LAUNCHES
310 nmi
(SPACE STATION
ALTITUDE PROFILE)
POWER CONVERSION INTERVALS
25 KW
75 KW
50 KW
250 nmi
STS
STS
STS
STS
STS
STS
SHUTTLE DEORBIT
OTV LAUNCH ASSIST
SHUTTLE DEORBIT
TETHER POWER GENERATION
○ = STS RENDEZVOUS WITH SS
● = TETHER DEORBIT/LAUNCH ASSIST

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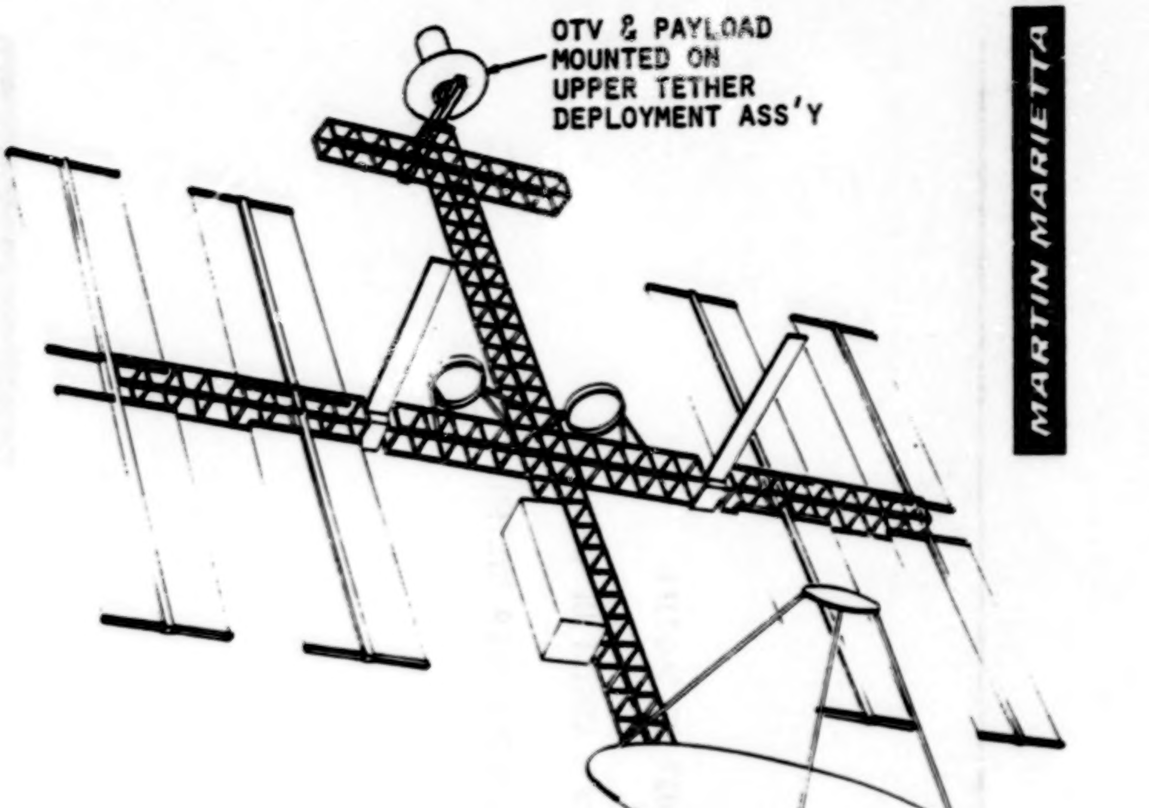
CONCEPT DESCRIPTIONS

PAIRED CONCEPTS

- A2 - TETHER DEORBIT OF SHUTTLE
- F - TETHER LAUNCH ASSIST OF OTV

DUAL MODE SPACE STATION DEPLOYER SYSTEM


OTV & PAYLOAD MOUNTED ON UPPER TETHER DEPLOYMENT ASS'Y
DUAL MODE TETHER REEL ASSEMBLY
SHUTTLE SHOWN READY TO BE TETHER DEPLOYED

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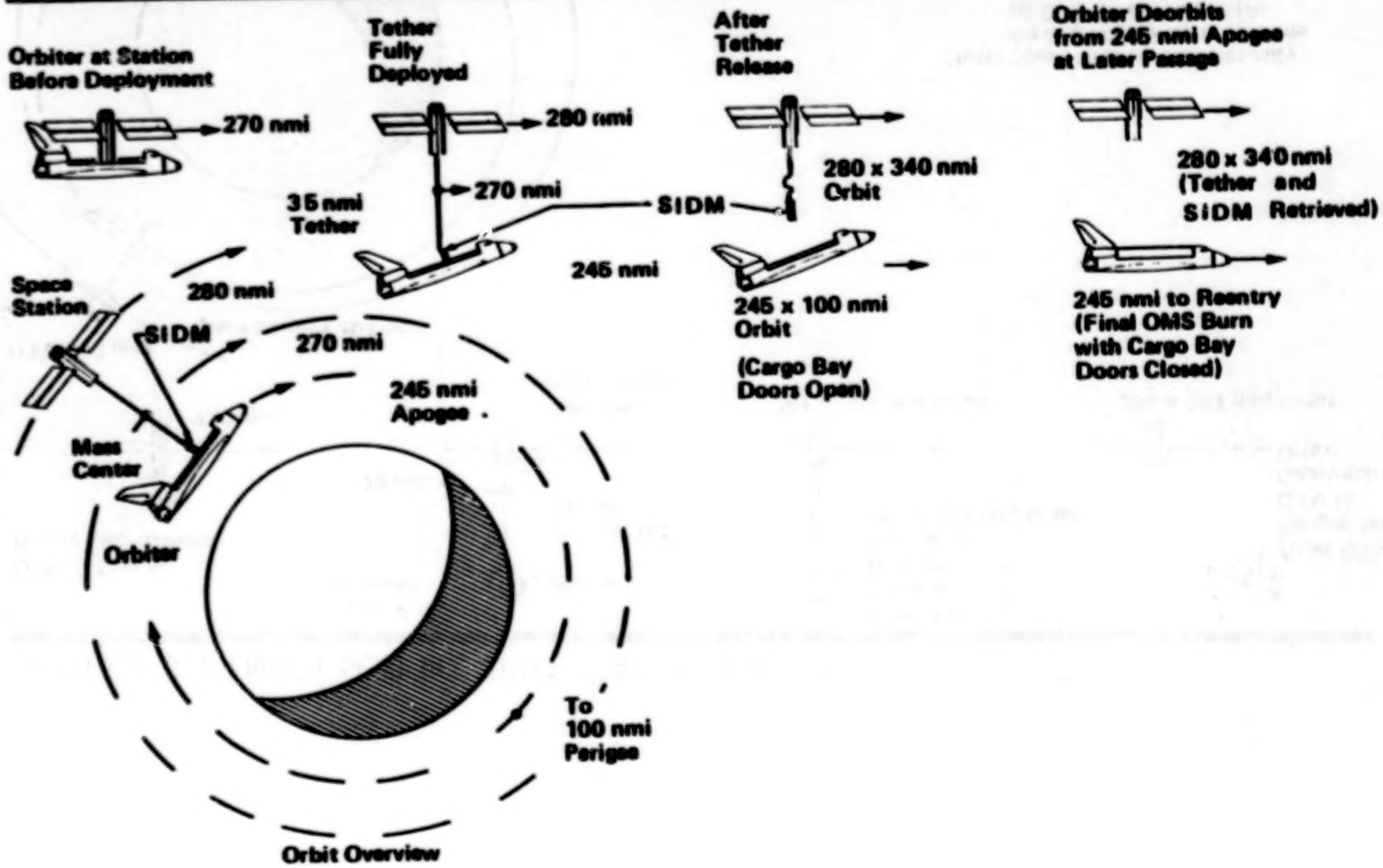
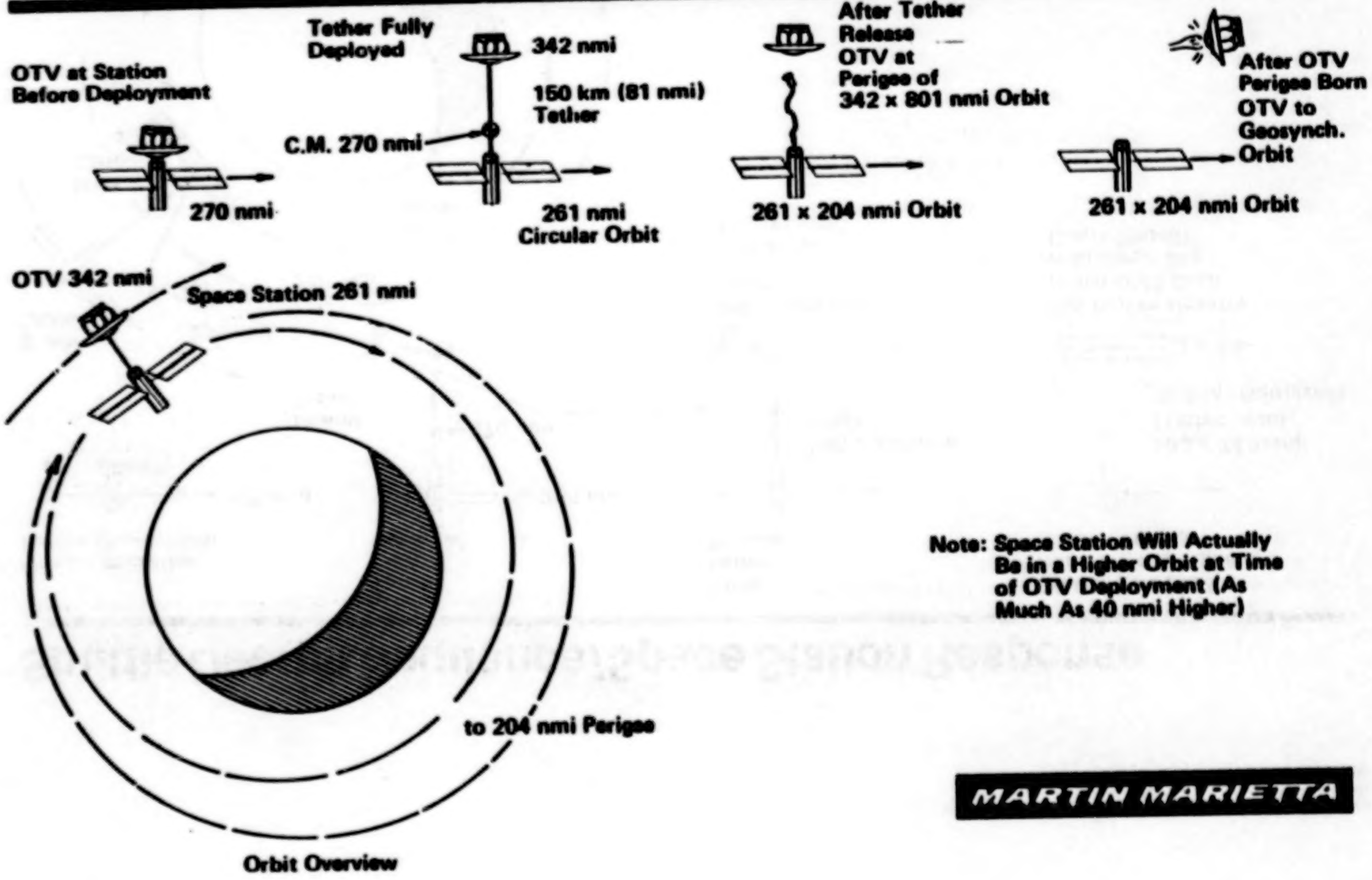
DUAL MODE TETHER DEPLOYMENT SYSTEM INSTALLED ON SPACE STATION

Shuttle Deorbit Sequence/Space Station Response


Orbiter at Station Before Deployment
270 nmi
Tether Fully Deployed
280 nmi
270 nmi
35 nmi Tether
SIDM
245 nmi
After Tether Release
280 x 340 nmi Orbit
245 x 100 nmi Orbit
(Cargo Bay Doors Open)
Orbiter Deorbits from 245 nmi Apogee at Later Passage
280 x 340 nmi (Tether and SIDM Retrieved)
245 nmi to Reentry (Final OMS Burn with Cargo Bay Doors Closed)
Space Station
280 nmi
SIDM
270 nmi
245 nmi Apogee
Mass Center
Orbiter
To 100 nmi Perigee
Orbit Overview

TETHERED OTV LAUNCH SEQUENCE/SPACE STATION RESPONSE


OTV at Station
Before Deployment
270 nmi
Tether Fully
Deployed
342 nmi
150 km (81 nmi)
Tether
C.M. 270 nmi
261 nmi
Circular Orbit
After Tether
Release
OTV at
Perigee of
342 x 801 nmi Orbit
261 x 204 nmi Orbit
After OTV
Perigee Born
OTV to
Geosynch.
Orbit
261 x 204 nmi Orbit
OTV 342 nmi
Space Station 261 nmi
to 204 nmi Perigee
Orbit Overview

Note: Space Station Will Actually Be in a Higher Orbit at Time of OTV Deployment (As Much As 40 nmi Higher)

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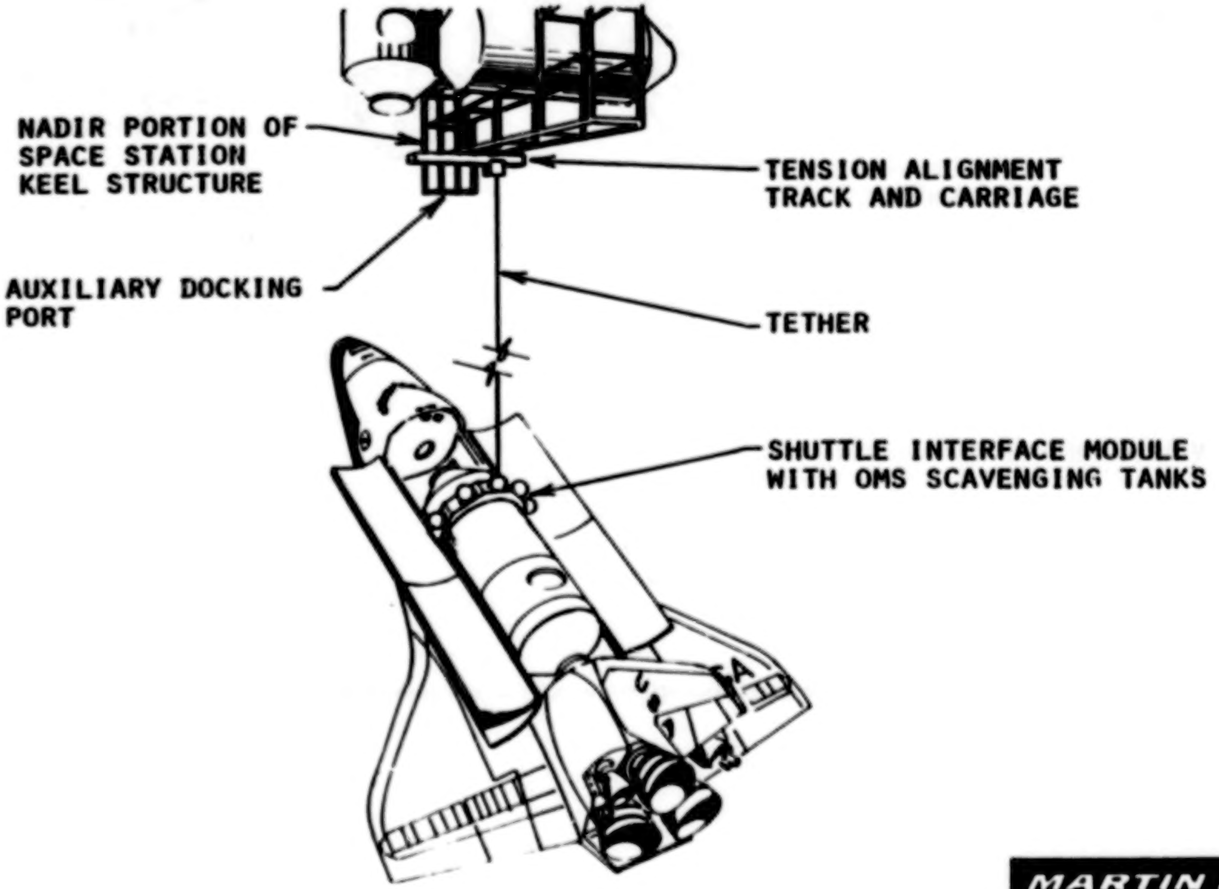
TETHER DEORBIT OF SHUTTLE


NADIR PORTION OF SPACE STATION KEEL STRUCTURE
TENSION ALIGNMENT TRACK AND CARRIAGE
AUXILIARY DOCKING PORT
TETHER
SHUTTLE INTERFACE MODULE WITH OMS SCAVENGING TANKS

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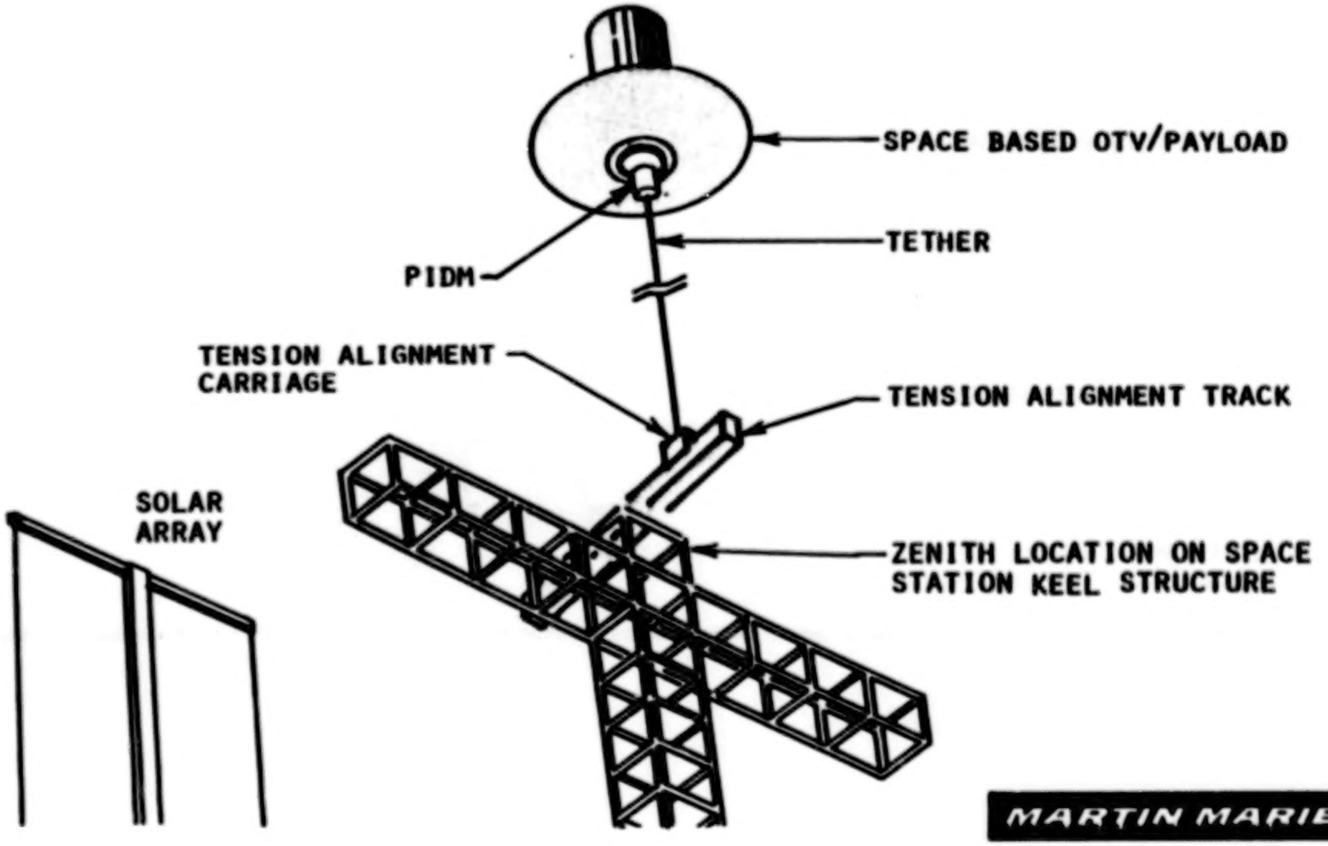
OTV TETHER LAUNCH ASSIST


SPACE BASED OTV/PAYLOAD
TETHER
PIDM
TENSION ALIGNMENT CARRIAGE
TENSION ALIGNMENT TRACK
SOLAR ARRAY
ZENITH LOCATION ON SPACE STATION KEEL STRUCTURE

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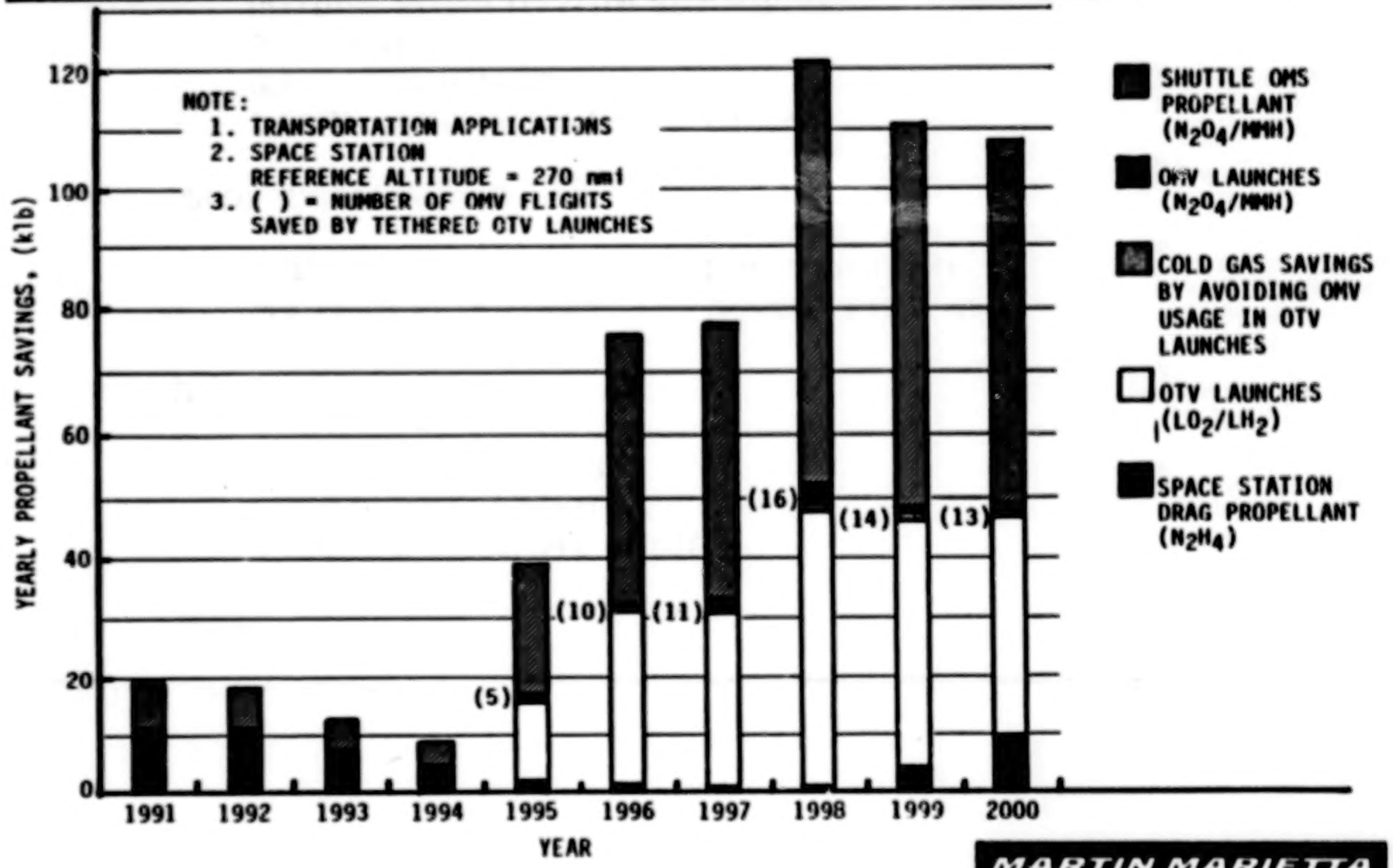
TECHNICAL ISSUES A2 AND F

- **TETHER**
  - DESIGN FOR ACCEPTABLE RECOIL
  - MULTIPLE REUSE DURABILITY
  - DEBRIS COLLISION HAZARD
- ENERGY MANAGEMENT
  - GENERATED BY DEPLOYMENT (A2/153KWH). F/366 KWH)
  - REQUIRED FOR RETRIEVAL (A2/11 KWH. F/29 KWH)
- SPACE STATION IMPACTS
  - INDUCED ACCELERATION LEVELS (10^{-2}G)
  - ORBIT PERTURBATIONS
  - STRUCTURAL STRESS
  - DEPLOYER SYSTEM LOCATION REQUIREMENTS
- OTV/TETHER INTERFACE
- OMS PROPELLANT SCAVENGING INTERFACE TO SHUTTLE

POTENTIAL YEARLY BENEFITS FROM SPACE STATION TETHER OPERATIONS



NOTE:
1. TRANSPORTATION APPLICATIONS
2. SPACE STATION REFERENCE ALTITUDE = 270 nmi
3. ( ) = NUMBER OF OMV FLIGHTS SAVED BY TETHERED OTV LAUNCHES

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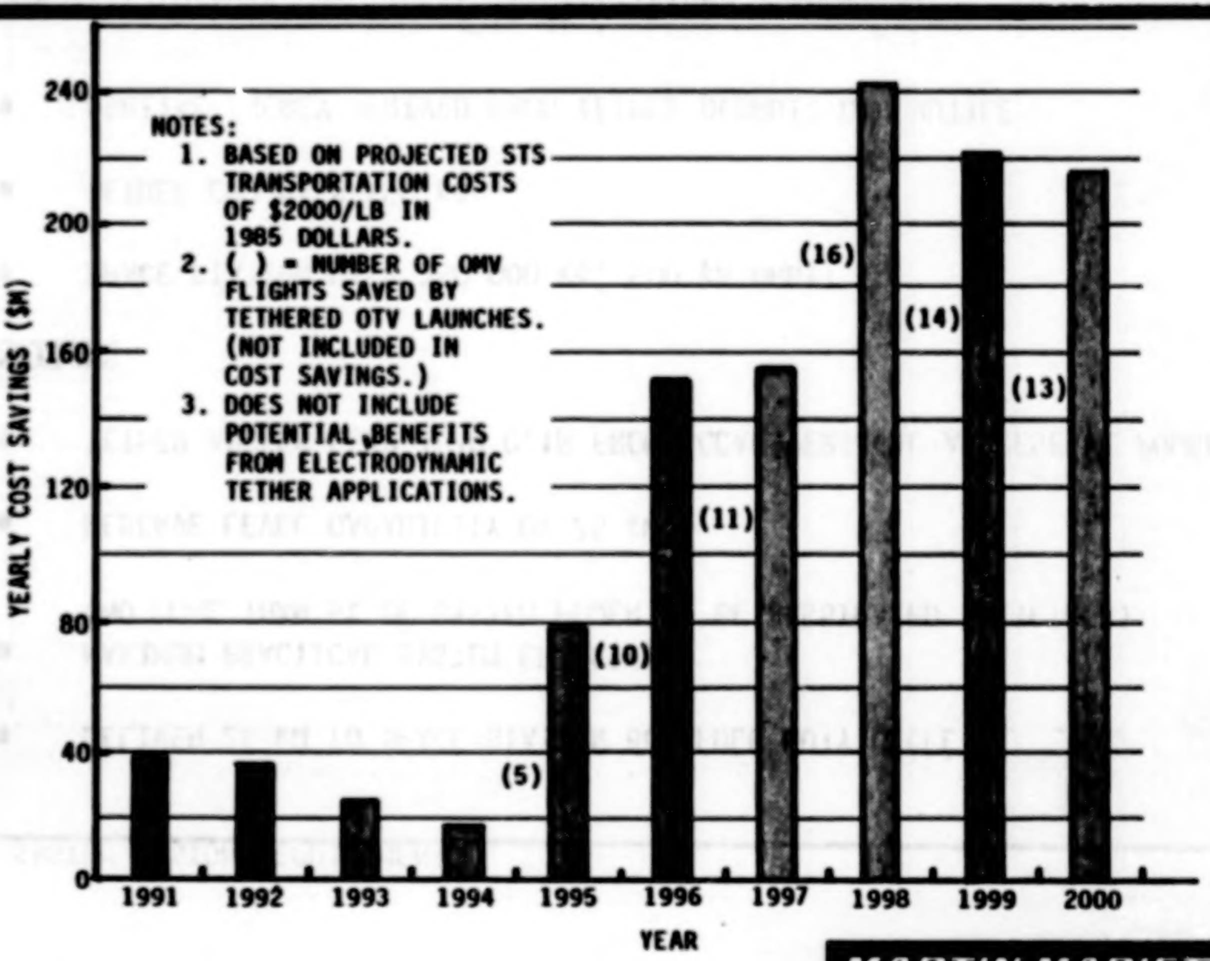
POTENTIAL COST SAVINGS FROM SPACE STATION TETHER OPERATIONS



NOTES:

1. BASED ON PROJECTED STS TRANSPORTATION COSTS OF $2000/LB IN 1985 DOLLARS.
2. ( ) = NUMBER OF OMV FLIGHTS SAVED BY TETHERED OTV LAUNCHES. (NOT INCLUDED IN COST SAVINGS.)
3. DOES NOT INCLUDE POTENTIAL BENEFITS FROM ELECTRODYNAMIC TETHER APPLICATIONS.

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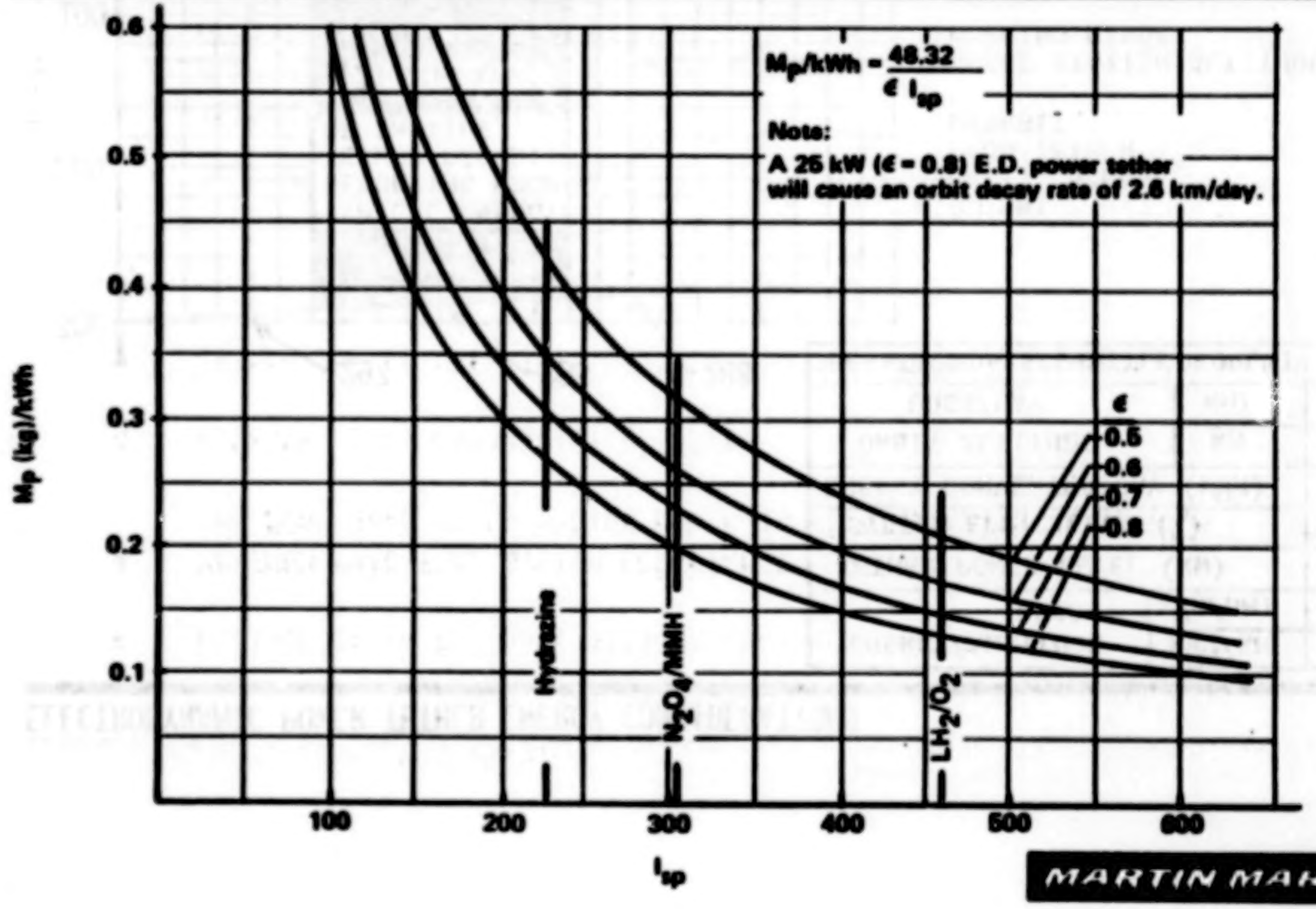
E2 - SYSTEM DESIGN REQUIREMENTS

- DELIVER 25 KW TO SPACE STATION BUS-FULL DUTY CYCLE
- MAXIMUM PRACTICAL SYSTEM EFFICIENCY
  (NO MORE THAN 5% OF SYSTEM POWER TO BE DISSIPATED IN TETHER)
- RESERVE LEVEL CAPABILITY OF 75 KW
- TETHER ANGLES LESS THAN 0.1R FROM LOCAL VERTICAL AT RESERVE POWER LEVEL

ASSUMPTIONS

- SPACE STATION MASS 250.000 KG. 500 KM ORBIT
- TETHER END MASS 500 KG
- ORBITAL ENERGY DERIVED FROM TETHER DEORBIT OF SHUTTLE

REBOOST PROPELLANT REQUIREMENTS

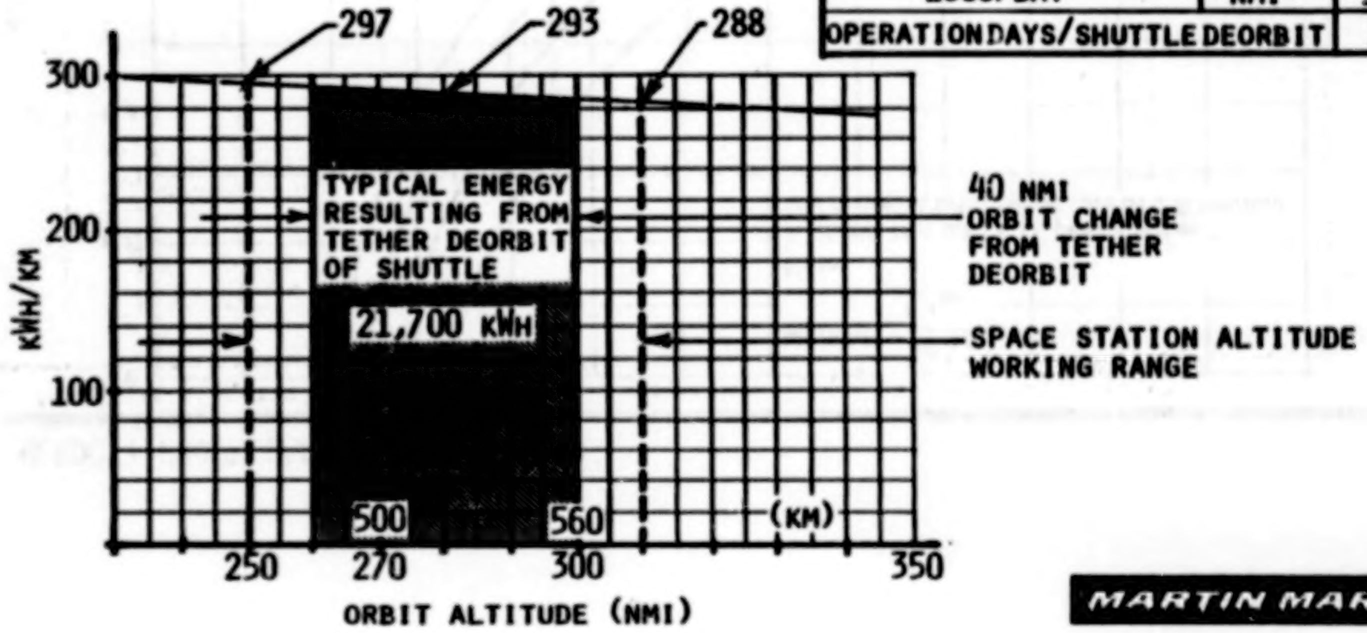


$M_p/\text{kWh} = \dfrac{48.32}{\epsilon\, I_{sp}}$

Note:
A 25 kW (ϵ = 0.8) E.D. power tether will cause an orbit decay rate of 2.8 km/day.

ELECTRODYNAMIC POWER TETHER ENERGY CONSIDERATIONS

ENERGY/ALTITUDE LOSS	KWH/KM	293 (AVG)	
	KWH/NMI	542 (AVG)	
TETHER POWER LEVEL (KW)		25	75
SYSTEM EFFICIENCY (%)		80	70
ENERGY CONVERTED/DAY (KWH)		750	2571
ORBIT ALTITUDE LOSS/DAY	KM	2.6	8.8
	NMI	1.4	4.8
OPERATION DAYS/SHUTTLE DEORBIT		29	8.4



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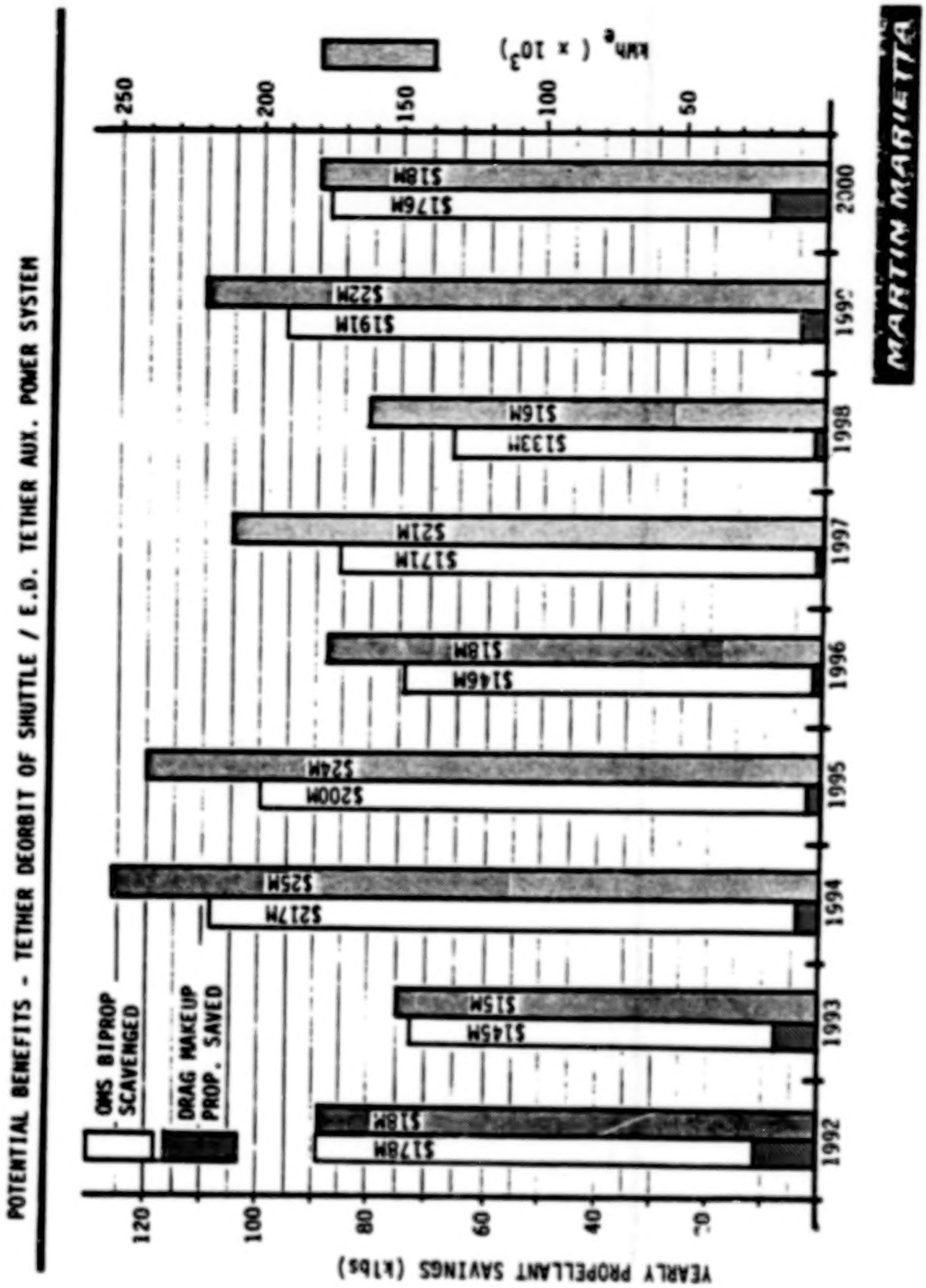
POTENTIAL BENEFITS - TETHER DEORBIT OF SHUTTLE / E.D. TETHER AUX. POWER SYSTEM



CONCLUSIONS AND RECOMMENDATIONS

W. Nobles

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CONCLUSIONS

- TETHER TECHNOLOGY HAS THE POTENTIAL TO SIGNIFICANTLY INCREASE THE PERFORMANCE EFFICIENCY OF THE INTEGRATED SPACE TRANSPORTATION SYSTEMS
    - SHUTTLE (OMS SCAVENGING, INCREASED PERFORMANCE ENVELOPE)
    - SPACE STATION (ORBIT MAINTENANCE, AUXILIARY POWER)
    - OTV (REDUCED PROPELLANT, INCREASED PERFORMANCE)
    - OMV (INCREASED PERFORMANCE ENVELOPE)
- POTENTIAL COST AVOIDANCE OF $250M + PER YEAR
- SURPLUS OF ANGULAR MOMENTUM AVAILABLE TO BE SCAVENGED FROM SHUTTLE. OTHER DEORBIT CANDIDATES AVAILABLE (WASTE PACKETS, E.T.'S)
- APPLICATION CONCEPTS ARE INTERACTIVE AND SHOULD BE CONSIDERED IN COMPLEMENTARY/COMPATIBLE SETS)
- ACCOMMODATION PROVISIONS MUST BE INCORPORATED INTO THE DESIGN OF ALL AFFECTED SYSTEMS
- OPERATIONAL IMPACTS ARE INHERENT AND MUST BE ACCEPTABLE TO AFFECTED SYSTEMS (ACCELERATION, ORBIT PERTURBATIONS)

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THE SCIENCE AND APPLICATIONS TETHERED PLATFORM (SATP) PROJECT

Pietro Merlina
Aeritalia

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THE SCIENCE AND APPLICATIONS TETHERED PLATFORM (SATP) PROJECT

F. Bevilacqua(1), P.Merlina(2) and A.Anselmi(3)

Aeritalia Space Systems Group, Torino, Italy

Background

The capabilities of tether systems in orbit are going to be demonstrated by the first three planned flights of the Tethered Satellite System (TSS),a joint US-Italian project now in the advanced development stage. As is well known, these test flights will investigate the properties of tether systems as low-altitude atmospheric research facilities and as electric power generators.

Many more applications of tethers have been proposed in the years since the ideas of the late G.Colombo started to circulate in the space community, some of which may be realized on the planned Space Station. In fact,applications of tethers to the Space Station, for both Space Station initial configuration and later extension of Space Station capabilities,are already the subject of a number of studies being performed both in the US and in Italy on the initiative of NASA and the Italian Space Agency/National Space Plan (PSN). Such studies are being conducted separately,with the purpose of testing a variety of concepts and approaches. A comparative analysis of results will allow the choosing of the most promising ideas for further development. The broad range of applications presently under study includes applications in electrodynamics,transportation, microgravity in addition to basic research.

Concerning the studies performed in Italy, PSN has decided to concentrate effort on those applications that show promise of an early use on the Space Station. The guidelines issued by PSN in its award to Aeritalia call for emphasis on two main subjects:

- a Science and Applications Tethered Platform (SATP), as a general-purpose,reconfigurable support for experimentation in science and technology; and
- a Tethered Teleoperator Manoeuvering System (TTMS), as a basic tool for a variety of operational uses ranging from payload launch and retrieval to Shuttle docking.

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(1) Director, Special Studies Department

(2) Study Manager, TSS Applications to the Space Station

(3) Advanced Studies Office

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The main thrust of the Aeritalia effort (80%) is to be devoted to the SATP Definition Study; the remaining 20% is to be devoted to an analytical study of the teleoperator concept leading to a feasibility assessment. Basic science applications are to take precedence over technological applications.

The SATP Definition Study is divided in two phases, the first devoted to assessment of applications and selection of the most promising of them,and the second to preliminary system design. An important part of the Study is identification of goals and requirements, and later design, of a functional scaled down replica of SATP to be used for testing the fundamental features of SATP on a dedicated Shuttle flight. At the end of the first study phase, recommendations will be submitted to PSN concerning the demonstration mission.

According to the initial concept, the SATP platform is to be located in one of the two stable libration points along the orbit radial direction. The tether may be up to 20 km long. Platform design should aim at modularity with a resources module including power, communication, attitude and thermal control and data handling subsystems, and a payload module for the experimental apparatus. Platform mass may be up to 50 tons and provisions should be made such that experiments lasting several months without interruption may be accommodated.

Inquiry on interests and requirements of potential SATP users

Since the main user of SATP will be the scientific community,it was determined important to start our study with an inquiry directed to potential users. As a first step, a "Call for Ideas" questionnaire was sent between March and April 1985 to some 200 representatives of selected scientific institutions in the USA and Europe.

It was realized from the start that this inquiry would require a long time in order to produce a level of detail in potential user proposals such that decisions could be based on them, with repeated rounds of interaction between Aeritalia and the addressees expected. However, only a period of eight months was available for the phase of the Definition Study leading to a selection among competing options. A compromise solution was found as follows. First, it was decided that the bulk of addressees should be chosen from among people already well acquainted with the properties of tether systems (in effect, all those having submitted proposals for the TSS payloads),so that learning time would be reduced to a minimum. As a second step, it was decided to immediately start study of those applications that, in the opinion of the study team, offered the most promise for SATP use, even though confirmation of the validity of choices would come only later. The ideas selected for initial study were: (1) a tethered platform for microgravity research, and (2) an astronomical observation platform requiring precise pointing.

Results of the inquiry. Response to the "Call for Ideas" has been encouraging, considering the limited audience selected and the short time available, with about 20 % returns to date. The most promising suggestions received are listed in Table 1. Communication with respondees is in progress in order to gain a better understanding of the requirements posed by the proposals.

Our initial assumption of a keen interest in the SATP project by the microgravity science community has been confirmed by the first round of contacts with potential users. This is evident from the quality and number of propo-

----

Microgravity & Materials Science

Biotechnology
Organic & Inorganic Crystal Growth
Radiobiology
Pharmaceutical Production
Measurement of Chemical Reaction Rate Constants
Scattering of Molecular Beams
Environmental Effects on Chemical Reactions & Macromolecules
Diffusion & Convection Phenomena

Plasma Physics & Electrodynamics

Electron Distribution of Ionospheric Plasma
Plasma Wave Propagation
Active Beam-Plasma Interaction
Mapping of Thermal Plasma Motion
Particle-Plasma Interaction
Power Generation

Geophysics & Atmospheric Physics

Cosmic Dust Collection
Simulation of Planetary Environments
Earth Observation by High-Resolution Solid-State Sensors
Geomagnetic Field Mapping
Crustal/Core Geomagnetic Field Anomaly Mapping
Measurement of Electric Fields in the Atmosphere (Thunderstorms)
Interplanetary Medium - Solar-Terrestrial Relationship

Table 1. Summary of Proposals for SATP Application from "Call for Ideas".

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sals, some of them actually coming from groups of scientists with interests in several disciplines. The stated reasons for such interest include:

- the large number of opportunities for investigators offered by a permanent facility;
- the availability of high power;
- the good projected quality of the environment, both from the point of view of dynamical stability and of freedom from contamination; and
- the inherent capability of tether systems of providing, if required, a gravity field variable both in magnitude (within a range limited by tether length) and in direction.

Response from the astronomy and astrophysics community has been limited thus far. Present-day and planned free-flying observatories appear adequate for the needs of these disciplines, whereas the advantages of a tether system for such applications is not as clear as for microgravity. Investigation of this application is nevertheless continuing, in the hope that once the capabilities of the system for stabilization and filtering of dynamical disturbances have been demonstrated, astronomers and astrophysicists will reconsider SATP value.

A considerable number of proposals concerns Earth and Planetary Physics and the Physics of the Atmosphere. Yet another group of proposals concerns applications of the electrodynamic tether. Many of them are similar to or develop ideas already submitted for TSS. However they would benefit from longer experiment times offered by SATP and the exploration of a region of space different from that accessible to the Shuttle. Since the selection of applications for the proof-of-concept Shuttle flight is the more urgent study task, and since proof of the electrodynamic tether concept is already the subject of TSS flights 1 and 3, applications requiring a conducting tether have been assigned a lower priority in the early part of the SATP study. However, further study will be devoted to them with the intent of making a separate proposal for electrodynamic systems including power generation.

System Studies

Independent of the issue of possible uses of SATP, a number of fundamental problems have to be investigated in order to assess the feasibility and usefulness of a tether system as a permanent facility on the Space Station. These concern the issue of lifetime and reliability of the system as a whole; the impacts of the tether system on the Space Station; and the sharing of resources between Station and SATP Platform.

Space Environment Problems. The lifetime of the tether system in orbit depends on the impact rate of meteorites and debris on the tether and on the degradation rate of tether construction materials under exposure to ionospheric atomic oxygen. Estimates of the impact probability are complicated by the considerable uncertainty in the actual and projected meteorites and debris flux. In addition, results are dependent on the way tether damage is modelled. According to the current models, man-made debris is the most important source of tether impact hazards for a 500-km orbit and a tether of 0.5 cm or larger diameter (Ref.1). Preliminary calculations lead to an estimated lifetime as low as 0.5 years for a single-strand aluminum tether of 1 cm diameter at a 95 percent probability level. Lifetimes longer by about a factor 3 are obtained for metals such as copper (Ref.2). Although model uncertainties might easily lead to calculated lifetimes differing by 2 orders of magnitude or more (Ref.3), such results do point to a fundamental problem that has to be investigated in detail before long-duration tether experiments are initiated. Regarding degradation, the corrosive effect of atomic oxygen on synthetic materials such as Kevlar and Kapton are well known. Possible solutions now being studied include metal coating and alternative tether materials. The results of the tether lifetime study will lead to recommendations for optimal tether diameter and composition, with impacts on system parameters such as tether mass and maximum length and hence techniques for carrying it into orbit and deploying.

Tether Systems for Space Station. An early assessment of the impact of a tether system on the Space Station is necessary in order that the Space Station retains the flexibility of employing tethers in its present design and later extension.The main areas of concern include displacement of the center of gravity of the Space Station complex, added drag and hindrance to visual observations and to operations by the STS and OMV in the proximity of the Station. None of these problems appears insurmountable if the possibility of housing tethers is taken into account in Space Station design from the start.

Resources Sharing. The extent to which SATP can be considered a user of Space Station resources, rather than providing for its own needs, is very important for SATP design. Transfer of power and data through the tether, if feasible, could lead to considerable simplification of system and subsystem design. Therefore studies have been initiated at Aeritalia on the use of the tether as a power line and as a communication link with optical fibers. Considerations include tether technology, safety, reliability and compatibility with the primary scientific uses of SATP.

The outcome of the activities so far described is expected to lead to the sizing of SATP and to establishing system technical requirements.

The Elevator System

Although the guidelines of the PSN award to Aeritalia call for a general-purpose platform, concept developments up to now have led to specialized designs for microgravity, precise pointing and electrodynamic applications. The issue of mutual compatibility of applications will be addressed when the requirements for each application are established to a sufficient level of detail.

In addition to cleanliness and high power, the requirements of microgravity applications call for a very stable dynamical environment with residual acceleration much smaller than 10^{-5} g as well as the possibility of modulating the gravity level or of obtaining differential measurements at locations with different gravity levels. This has led to the consideration of a moving Elevator along a tether deployed to a fixed length. Such a system has already been proposed as a solution to the complex control problems associated with retrieval of the entire tether system (Ref. 4).

Since radial acceleration changes with position along the tether (at a rate of approximately 3.7×10^{-4} g per km of distance from center of gravity), the Elevator would be able to attain residual gravity levels different from zero. The minimum residual acceleration is attained with the mobile laboratory located in the Space Station - Tether System orbit center (the point where gravity exactly balances centrifugal acceleration).

After consideration of sources of dynamical disturbances, a reasonable design objective appears to be attainment of an acceleration upper limit of 10^{-6} g. The residual acceleration is mostly due to the harmonics of the Earth gravity field, to residual librations and to thermal longitudinal oscillations.The attainment of such a goal is dependent on the control of libration amplitudes to less than 10^{-3} radians and effective insulation of the microgravity facility from disturbances originating in the Space Station and propagating along the tether.

Investigation of the Elevator concept at Aeritalia is continuing, including configuration studies and Elevator translation methods.

The Pointing Platform

The idea of using the gravity gradient tension in the tether to provide two-degree-of-freedom attitude control of a pointing platform originates with a proposal by L.G.Lemke of

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NASA Ames Research Center (Ref. 5). The natural orientation of the tether system along the vertical makes it suitable not only for Earth observation purposes, but also for astronomical observations if SATP platform were endowed with an independent capability for changing pointing direction away from the vertical. As with other possible SATP applications, such an observatory would take advantage of the facilities of the Station for maintenance and repair while being isolated from contamination and mechanical disturbances.

The pointing platform concept relies on the tether tension itself to provide a restoring torque against disturbances via displacement of the SATP attachment point. In principle, this provides the ability to control disturbances coming from libration and displacements of the center of gravity aboard the platform. Computer simulation of the control in an idealized case assuming perfect mechanism response and error-free attitude measurement shows that stabilization within arcsecond magnitude can, in principle, be achieved on an actual system.

From a technological point of view the problem is to handle even the most minute disturbances by means of a relatively strong force such as tension, so as to satisfy the tight accuracy requirements of a fine-pointing application. The areas of present investigation include design of the movable attachment mechanism, identification of a robust control law allowing for sensor and hardware errors, and hardware definition.

The Demonstration program

The first phase of the SATP Definition Study will end with recommendations toward development of a Shuttle flight test of the performance of the basic features of SATP. The demonstration should provide the confidence needed to initiate a full-scale effort devoted to implementation of a tethered platform on the Space Station. The test flight could be scheduled as early as 1989.

Both cost and schedule constraints impose a necessity to re-use to the maximum possible extent the hardware already under development for the STS-based TSS flights. In particular, use of the same deployer is mandatory. Therefore the demonstration should be a proof-of-concept rather than a full test of SATP in a down-scaled configuration.

Progress of the Aeritalia work so far indicates that the demonstration may concern two concepts:

- a demonstration of the elevator as a means of achieving a residual acceleration field at center of force suitable for the microgravity-lab application: and

- a demonstration of the SATP movable attachment point concept for the fine pointing application.

Regarding the microgravity application, one is mainly concerned with perturbing accelerations and disturbances propagating along the tether. These are originated mainly by the Space Station and by Elevator motion. Disturbances coming from these sources excite vibrations with a rate of damping increasing with frequency, but also a series of resonances with peaks not easily modelled because of the complexity of phenomena involved. Another unknown in the problem is the magnitude of the expected natural damping and/or what methods could be used for actively attenuating the disturbances. A Shuttle test of an Elevator model would therefore be valuable for studying such phenomena, evaluating the effects and testing on the field practical disturbance suppression techniques.

Concerning the fine-pointing application, the demonstration will address attitude motion and libration-control properties of the movable attachment point concept. The main problem of this new means of attitude stabilization is devising suitable control techniques when system dynamics as complex as those outlined above are present. Tether tension represents both the control force and the major source of disturbances. The control system must be able to neutralize tether disturbances and to provide the small control torque needed to counteract external perturbations. The control strategy could be of a double-loop type. Hardware and software optimization would benefit from an on-orbit test due to the complexity of the overall system dynamics.

One fundamental issue concerns the extent to which a demonstration mission of a scaled down SATP with the Shuttle in the usual 300-km orbit constitutes proof-of-concept of a full-scale mission in a 500-km orbit. Similarity theory requires identification of suitable dimensionless parameters characteristic of each physical aspect one wants to model, and scaling such that those parameters are left unchanged. In practice, implementation of full or partial similarity conditions may prove unpractical or unfeasible. Even in this case, a STS flight test would be significant as a means of validating the mathematical model describing the dynamics and control, by comparison between predicted and actual system behaviour.

Conclusions

The SATP Project Definition Study is now about midway through its first phase. The analyses conducted up to now have led to an appraisal of users interest in the project and to a deeper understanding of the problems associated with large, long-lived tether systems in space. In addition, two specialized platform designs, devoted to microgravity and precise pointing applications, are being studied because of their potential usefulness and the promise of technical feasibility.

The second phase of the Definition Study will mainly be concerned with developing configuration options for a Shuttle-based demonstration flight devoted to the validation of the above mentioned specialized platform designs. Further development, subject to a positive decision on the continuation of the project by NASA and the Italian Space Agency, may lead to the realization of such a flight as early as 1989.

References

1. Kessler,D.J. and Cour-Palais, B.G. (1978) J.Geophys. Res. 83,2637
2. Ciardo, S. (1985), Aeritalia Internal Note
3. Kessler,D.J. (1985), private communication
4. Kane,T.R. (1984), J.Astronautical Sci. 32,351
5. Lemke,L.G. (1984), Proposal to NASA

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TECHNOLOGY AND TEST

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The Technology Applications in Space Working Group was established by NASA to evaluate proposed tether applications and to formulate and make recommendations relative to the tether applications program. The initial proposals addressed by this group were the recommendations from the first Tether Workshop held in Williamsburg, Virginia, in 1983. The TAS Working Group has reviewed the tether applications program annually and published a program plan each year since its creation. This program plan summarizes the results contained in the individual project plans produced by the group's members in each of the tether applications discipline areas:

1. Electrodynamic Interactions
2. Transportation
3. Gravity Utilization
4. Constellations
5. Technology and Test
6. Science Applications

which were, and are, the basis of the workshop organization.

As a member of the TAS Working Group and representing NASA's Langley Research Center, which is a technology center, I have been responsible for the definition of the Technology and Test of Tether Applications Project Plan. This plan is specifically concerned with the definition of the technology developments and test requirements associated with the implementation of the various TAS discipline programs as well as tether applications that could provide technology-related data. The continuing recommendations contained in both the workshop report and the annual Technology and Test project plan are associated with the development of the technology relative to:

1. Tether Materials and Configurations
2. Tether System Dynamic Simulation Capability
3. Tether System Instrumentation (System performance monitoring and control)
4. TAS Program Related Science Instrumentation
5. Atmospheric/Aerothermodynamic (STARFAC) tethered system research
6. TAS Discipline Program Accomplishment, i.e. System Components

Figure 1 provides a summary of the TAS Technology Issues for each of the disciplines as well as the recommended technology mission--Atmospheric/Aerothermodynamic Technology.

As a result of the near-term implications of the electrodynamic tether (TSS-1 and Space Station potential) and atmospheric/aerothermodynamic tethered system research (TSS-2 and STARFAC), these two applications have received high priorities, and the development of the technology required to advance/implement these concepts is being strongly recommended by the TAS Working Group.

To enable these tether applications, design and development programs have been recommended and are presently underway relative to the demonstration of the hollow cathode concept which is an enabling electrodynamic tether mission technology. Additionally, studies relative to tether insulation and insulation coatings are being initiated. Finally, the realization of the electrodynamic tether concept's potential requires the development of high voltage components and high performance tether conductors as well as a tether damage detection capability and performance monitoring and control instrumentation. Such instrumentation is critical to all tether applications and is considered to be an enabling technology.

Relative to the Atmospheric/Aerothermodynamic tether application, studies have been underway to establish the feasibility and define the limitations of the Shuttle Aerothermodynamic Research Facility (STARFAC) or tethered wind-tunnel concept. These studies have established the feasibility, but not the limitations, to date. The studies have also identified a need for a high-temperature tether to extend the research capability of the concept to altitudes compatible with data required by on-going and proposed NASA flight programs. As is the case with the electrodynamic tether, the success of the STARFAC is contingent on the development of the required engineering instrumentation for system performance monitoring and control. Additionally, since STARFAC is a technology research concept, its success is dependent on the development of the required research/science instrumentation.

Finally, the TAS Working Group has recognized the need for a capability/technique with which to accomplish tether concept tests and simplfied missions which do not require the TSS. The concept of an expendable tether system is being studied to satisfy this need.

The NASA input, then to the present (1985) tether workshop, will provide a detailed review of the concepts and programs described above as follows:

1. TSS-2 Atmospheric/Aerothermodynamic Proposal/Status
2. STARFAC - Program Definition
    a) Mission Simulation Results
    b) Instrumentation Definition Study Results
3. Tether Materials Study Results
4. Expendable Tether Concept
5. Electrodynamic Tether Technology

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APPLICATION	TECHNOLOGY ISSUES
Electrodynamic Interaction	Hollow Cathode High Voltage Components High Performance Tether Conductors Tether Insulation/Insulation Coatings Tether Damage Detection
Gravity Utilization (Variable and/or Artificial Gravity)	Gravity Level Instrumentation Disturbance Damping Tether Tether Crawler Mechanism Tether Repair Tether Damage Detection
Constellations	Tether Materials/Configurations Tether Damage Detection Tether Repair
Transportation	Tether Materials/Configurations Tether Damage Detection Tether Repair
Technology & Test	Tether Materials/Configurations Tether System Dynamic Simulation/Mission Modeling Tether Monitoring and Control Instrumentation
- Technology Mission	Atmospheric/Aerothermodynamic Technology (Shuttle Tethered Aerothermodynamic Research Facility - STARFAC) o High Temperature Tether o Research Instrumentation o System Monitoring and Control Instrumentation

Fig. 1. Tether Applications in Space.

NASA

TECHNOLOGY AND TEST

PROGRAM STATUS

- TSS-2 ATMOSPHERIC / AEROTHERMODYNAMIC PROPOSAL
- STARFAC DEFINITION STUDY
  - MISSION SIMULATION RESULTS
  - INSTRUMENTATION STUDY RESULTS
- TETHER MATERIALS STUDY RESULTS
- EXPENDABLE TETHER CONCEPT AND MISSION STUDY RESULTS
- ELECTRODYNAMIC TETHER TECHNOLOGY DEVELOPMENT
  - HOLLOW CATHODE
  - TETHERS
  - COMPONENTS

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TETHERED CONSTELLATIONS

Enrico Lorenzini
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First Day Presentation at the Venice Workshop

Tethered Constellations

Speaker: Dr. E. Lorenzini, Smithsonian Astrophysical Observatory

This presentation briefly addresses the studies that have been carried out so far on Tethered Constellations since the last Tether Workshop in Williamsburg, Virginia in 1983.

A definition of "tethered constellation" is required since there is sometimes a great deal of misunderstanding. A tethered constellation is any number of masses/platforms greater than two connected by tethers in a stable configuration.

Viewgraph #1

In general we can have 1-D, 2-D and 3-D constellations. In order to design a passively stabilized tethered constellation we must resort to every non-negligible force or gradient that is available in low orbit. The vertical gravity gradient is the strongest of all but there are also differential air drag, electrodynamic forces, J_{22} gravity components and others. A combination of the above mentioned forces can be exploited in order to provide a stable configuration.

Viewgraph #2

The study plan on tethered constellations was very well defined by NASA at the workshop in Williamsburg: tethered constellations were divided in two different categories. On the right side of the figure there are the so-called "dynamic constellations." The adjective "dynamic" is not completely appropriate, however their name means that a tethered constellation is rotating with respect to the orbiting reference frame. On the left side of the same figure there are the "steady state constellations." Again the adjective "steady state" is somewhat misleading because these constellations rotate at orbital rate so that "steady state" must be intended with respect to the orbiting reference frame. In this category there are 1-D, vertical constellations like the one on the far left of the figure; the so-called "fish-bone" constellations, in the center of the figure and the 1-D, horizontal constellations.

Viewgraph #3

Tethered constellations can be used for many different applications such as the micro-g/variable-g laboratory or the multi-probe laboratory where separate probes are distributed along a vertical tether in order to measure gradients of geophysical quantities. These two systems can be operated either by the Shuttle or by the Space Station. A possible strategy is to use the Shuttle for testing the system and the Space Station for the permanent facility. Another application of tethered constellations is the ULF/ELF phased antenna; namely three masses are on the tether and a current is flowing alternatively in the upper and lower tether in order to inject a square electromagnetic wave into the ionosphere. Beside the issues related to the detectability of the signal on the ground, this system requires an investigation of the constellation dynamics forced by the electrodynamic drag and thrust associated with the wave injection process.

The space elevator is an application studied by Aeritalia. A tether with an end mass/platform is attached to the Shuttle providing a rail for the motion of the space elevator. The space elevator can be used to transport materials to and from the end mass that in this case is a storage area. The space elevator, when operated near the orbit center of the entire system (zero acceleration point) can be used as a micro-g/variable-g laboratory.

With reference to the Space Station, possible attachment points of tethers to the Space Station are in the upper deck and lower deck. If two tether systems (one up and one down) are operated simultaneously the resulting configuration is a tethered constellation.

The last category of applications listed in the viewgraph is formed by free-flying tethered constellations; free-flying meaning that they are not attached to a mother station. An example are the 2-D constellations: four or more masses are kept in relative fixed positions by tethers in order to have a physical separation of activities within the same space vehicle.

Another idea, generated at the Smithsonian Astrophysical Observatory, is the variable baseline tethered interferometer. A tethered system with three masses rotates on a plane perpendicular to the line of sight to the source. The two end masses carry the mirrors while the interference fringes of the incoming signal are measured at the platform in the middle. By varying the tether length (variable baseline) a two-dimensional scanning of the source is performed.

In the area of the 2-D constellations, electrodynamically stabilized constellation can be used to provide an external stable frame for giant reflectors.

Viewgraph #4

This viewgraph summarizes the studies that have been performed on the various types of constellations. The major goal of the investigation was to access feasibility of different configurations. Most of the studies were focused lately on the 1-D, vertical constellations which appear to be the most promising configurations.

Viewgraph #5

Some general comments on the stability of tethered constellations are shown in this viewgraph. 1-D, vertical constellations are definitely preferable from the stability point of view to 1-D, horizontal constellations: the vertical gravity gradient dominates the differential air drag at Space Station altitude while at lower altitude (150-200 km), where differential air drag can become relatively strong, the orbital lifetime is very limited. Regarding the 2-D constellations a convenient way for achieving a stable configuration is by exploiting the gravity gradient for overall attitude stability (constellation's minimum axis of inertia must be along the local vertical) while differential forces such as air drag or electrodynamic forces are used to stretch the constellation horizontally in order to provide shape stability.

Viewgraph #6

Stability constraints for the 1-D, horizontal constellations are shown in this viewgraph. The fundamental parameter is the differential ballistic coefficient of the two end bodies that in the case of a massive front body and a voluminous rear body (balloon) is equal to the ballistic coefficient of the latter. The table shows maximum tether lengths for static stability along the local horizon, and orbital decay rates. Results are strongly dependent on the atmospheric density conditions. By assuming a ballistic coefficient of 10 m^2/kg for the rear balloon (twice as much the Echo balloon's ballistic coefficient), the table shows that tether lengths and orbital lifetimes are contrasting requirements and they are never sufficiently satisfied in the altitude range of interest. In general it must be said that a passively stabilized horizontal constellation is justified by a long lifetime mission requirement whereas a constellation designed for a short lifetime can more easily use active stabilization.

Viewgraph #7

The "fish-bone" configuration was the first proposed 2-D constellation. A "fish-bone" constellation can be reduced to an equivalent 1-D, horizontal constellation if the overall ballistic coefficient of the rear leg (ballons + tethers) and the front leg are respectively concentrated at the end of the horizontal tether. Actually the stability of a "fish-bone" constellation is even more marginal than a comparable 1-D, horizontal constellation because a lower, rear (equivalent) ballistic coefficient is attainable in the "fish-bone" due to the greater complexity of the system.

Viewgraph #8

This viewgraph shows two of the alternative configurations for 2-D constellations that we have developed at SAO. Both of them use differential air drag for the shape stability while the gravity gradient provides the overall attitude stability only, in accordance with the comments expressed in viewgraph #5. They are therefore called drag stabilized constellations or DSC. Differently from the "fish-bone" constellations air drag and gravity gradient do not fight each other in a DSC.

Viewgraph #9

2-D configurations similar to those previously presented are shown in this viewgraph. The first one on the left is like the quadrangular DSC except that a current flowing in the outer loop provide the shape stability of the system. The current interacts with the earth magnetic field and it generates electrodynamic forces that, depending on the current direction, push the constellation perpendicularly to the local current like the air inside a balloon. They are called electrodynamic stabilized constellations or ESC. The configuration on the right uses the same principle with a different geometry. The outer loop is acted upon by distributed gravity gradient forces and distributed electrodynamic forces. The two lumped masses provide extra attitude stability without affecting the shape. The resulting shape is very similar to an ellipse apart from being more flat at the apeces so that these constellations are called pseudo-elliptical constellations or PEC. PEC's can provide a stable external frame for a two-dimensional reflector or similar, in space.

Viewgraph #10

The studies on tethered constellations are now concentrating on the 1-D, vertical constellation with 3 masses for micro-g/variable-g applications (from now on called g-platform). The g-platform is operated from the Space Station whose mass, at the time this investigation started, was 90.6 metric tons. A 10 km tether is attached to the Space Station and ballasted at the end with a 9.06 metric ton mass. The center of the orbit (zero-g acceleration point) of the system is 1.2 m lower than the system c.m. The center of the orbit is the point where the micro-g laboratory is located for conducting micro-g experiments, whereas the laboratory will be moved up or down along the tether to perform variable-g experiments.

Viewgraph #11

In the effort to access what acceleration level is attainable with such a system, the constellation dynamics has been simulated over some orbits. Simulations are preliminary and perturbations such as transverse wire dynamics and Space Station orbital variations are not accounted for yet. Nevertheless this simulations give an idea of what order of magnitude for the acceleration has to be expected at the best of the system performance. In the simulations an acceleration level around 10^{-8}g has been attained; this value being primarily limited by the J_2 component of the gravity field. The J_2 component forces the system to librate and also directly and indirectly (through libration) stretches the tethers longitudinally. Longitudinal tether vibrations accounts for the behavior of the radial acceleration component shown in the figure. The low frequency variation is not abatable (being the steady state component) while the high frequency components can be damped out by appropriate longitudinal dampers (missing in the present simulation).

Viewgraph #12

Further studies on the g-platform have been carried out including the deployment of the system from the Space Station and the damping of longitudinal, librational and transverse (1^{st} mode) vibrations. Successful deployment in less than 3.5 hours has already been demonstrated while appropriate damping algorithms have been devised.

Viewgraph #13

The conclusions are therefore as follows. The 1-D, horizontal, passively stabilized constellations have been ruled out on the basis of what pointed out before. "Fish-bone" constellations have been similarly ruled out, whereas alternative, stable, 2-D configurations have been devised such as the ESC's, the DSC's and PEC's. Typical dimensions for these constellations are 10 km (horizontal) by 20 km (vertical) with balloon diameters around 100 m in the case of a DSC and a power consumption around 7 KW for an ESC or PEC.

Viewgraph #14

1-D, vertical constellations are very stable with a variety of different applications. A 3-mass system can be conveniently used as a micro-g/variable-g laboratory. Such a system shows promises of providing an acceleration level better than the 10^{-5}g level attainable on board the Space Station plus the additional, important option of having a variable/controlled g-level whenever desired.

1-D, vertical constellations with many masses along the tether can be used as a multi-probe system to collect simultaneous data at different locations along the local vertical. The capability of measuring geophysical gradients would be greatly enhanced by such a system.

Tethered constellations are showing many intriguing and unexpected capabilities: all the necessary ingredients are by now available and some of the options are already taking shape. Additional fantasy could transform this already numerous dishes into a tremendous menu.

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WORK DONE UNDER CONTRACTS:
NAS8-35497 NASA/MSFC
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RH4-394019 MMC

TETHERED CONSTELLATIONS IN SPACE

BY

ENRICO LORENZINI

PRESENTED TO:

APPLICATIONS OF TETHERS IN SPACE WORKSHOP
VENICE, ITALY
15-17 OCTOBER 1985

SMITHSONIAN ASTROPHYSICAL OBSERVATORY

GENERAL

- ANY GENERIC DISTRIBUTION OF MORE THAN TWO MASSES IN SPACE CONNECTED BY TETHERS IN A STABLE CONFIGURATION IS A TETHERED CONSTELLATION

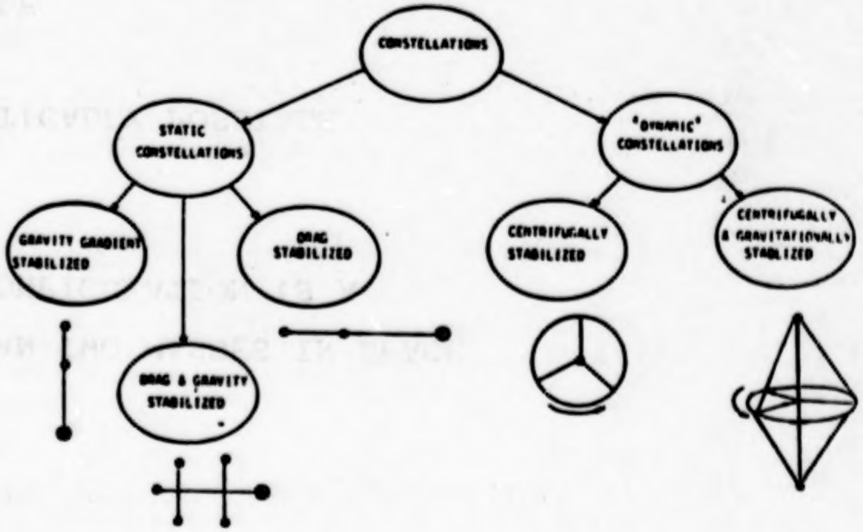
- 1-D, 2-D, 3-D CONFIGURATIONS THEORETICALLY POSSIBLE

- STABILIZING FORCES CAN BE FOR EXAMPLE
  - VERTICAL GRAVITY GRADIENT
  - DIFFERENTIAL AIR DRAG
  - ELECTRODYNAMIC FORCES
  - J_{22} GRAVITY COMPONENT
  - CENTRIFUGAL FORCES

- A COMBINATION OF THE ABOVE MENTIONED FORCES CAN BE EXPLOITED IN SOME CONFIGURATIONS

CONSTELLATION STUDY PLAN

- STUDY PLAN INITIALLY DEFINED BY NASA APPLICATIONS OF TETHERS IN SPACE WORKSHOP GROUP
- "DYNAMIC" CONSTELLATIONS HAVE NOT BEEN PURSUED ON THE BASIS OF FEASIBILITY CONSIDERATIONS
- STATIC CONSTELLATIONS HAVE BEEN ANALYZED AS WELL AS ALTERNATIVE CONFIGURATIONS
- MAJOR AREAS OF INVESTIGATION
  - CONFIGURATION STABILITY
  - STATION-KEEPING DYNAMICS
  - DEPLOYMENT STRATEGICS
  - MODAL VIBRATION DAMPING


CONSTELLATIONS
STATIC CONSTELLATIONS
"DYNAMIC" CONSTELLATIONS
GRAVITY GRADIENT STABILIZED
DRAG STABILIZED
DRAG & GRAVITY STABILIZED
CENTRIFUGALLY STABILIZED
CENTRIFUGALLY & GRAVITATIONALLY STABLIZED

PRESENTLY PROPOSED APPLICATIONS FOR TETHERED CONSTELLATIONS

- ATTACHED TO THE SHUTTLE
  - MICRO-G/VARIABLE-G LAB: 1-D, 3-MASS
  - MULTI-PROBE LAB FOR MEASUREMENT OF GEOPHYSICAL GRADIENTS: 1-D, 4 OR MORE-MASS
  - TESTING OF ULF/ELF PHASED LONG ANTENNAE: 1-D, 3-MASS
  - SPACE ELEVATOR FOR TRANSPORTING MATERIALS TO THE END MASS: 1-D, 3-MASS
- ATTACHED TO THE SPACE STATION
  - MICRO-G/VARIABLE-G LAB: 1-D, 3-MASS
  - MULTI-PROBE LAB: 1-D, 3 OR MORE MASS
  - STORAGE OF MATERIALS/FLUIDS SERVICED BY THE SPACE ELEVATOR: 1-D, 3-MASS
  - DUAL DEPLOYER, ONE PER SIDE OF THE SS: 1-D, 3-MASS
- FREE-FLYING TETHERED CONSTELLATIONS
  - SEPARATION OF DIFFERENT ACTIVITIES IN A PHYSICALLY CONNECTED CLUSTER: 2-D, MULTI-MASS
  - OPTICAL INTERFEROMETRY: 1-D, 3-MASS, ROTATING
  - GIANT REFLECTORS IN SPACE: 2-D

TETHERED CONSTELLATIONS UNDER INVESTIGATION

- 1-D, HORIZONTAL CONSTELLATIONS
  - STABILITY ANALYSIS
- 2-D, "FISH-BONE" CONSTELLATIONS
  - STABILITY ANALYSIS
- 2-D, GENERIC CONSTELLATIONS
  - ALTERNATIVE CONFIGURATIONS
  - STABILITY ANALYSIS
- 1-D, 3-MASS VERTICAL CONSTELLATIONS
  - STATION-KEEPING DYNAMICS
  - DEPLOYMENT STRATEGY
  - MICRO-G APPLICATIONS
  - DAMPING OF MODAL VIBRATIONS

GENERAL COMMENTS ON CONSTELLATION STABILITY

- 1-D CONSTELLATIONS
  - GRAVITY GRADIENT DOMINATES DIFFERENTIAL AIR DRAG AT SS ALTITUDE
  - AT VERY LOW ALTITUDE (150 KM) DIFFERENTIAL AIR DRAG IS STRONG BUT ORBITAL LIFETIME IS VERY LIMITED
  - 1-D, MULTI-MASS VERTICAL CONSTELLATIONS ARE PREFERABLE FOR GOOD STABILITY
- 2-D CONSTELLATIONS
  - EXPLOIT THE GRAVITY GRADIENT FOR OVERALL ATTITUDE STABILITY (CONSTELLATION'S MINIMUM AXIS OF INERTIA MUST BE VERTICAL)
  - RESORT TO DIFFERENTIAL DRAG OR ELECTRODYNAMIC FORCES TO STRETCH THE CONSTELLATION HORIZONTALLY IN ORDER TO PROVIDE SHAPE STABILITY

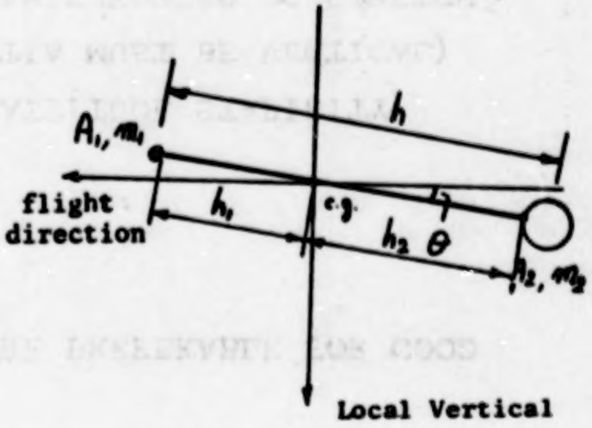
DRAG STABILIZATION LIMITS FOR SINGLE-AXIS HORIZONTAL CONSTELLATIONS

$$\text{AREA/MASS} = A/M_2 = 10\ \text{M}^2/\text{KG}$$

	Minimum Atmo. Density Exospheric Temp. = 600K		Maximum Atmo. Density Exospheric Temp. = 1100K	
z(km)	h_{max}(m)*	$\frac{da}{dt}$ (km/day)**	h_{max}(m)	$\frac{da}{dt}$ (km/day)
150.	2.31×10^5	2.84×10^3	3.23×10^5	3.97×10^3
200.	1.89×10^4	2.29×10^2	4.79×10^4	5.82×10^2
300.	5.47×10^2	7.05	4.51×10^3	5.36×10^1
400.	3.57×10^1	0.42	7.58×10^2	8.80
500.	3.64	0.04	1.61×10^2	1.83

*h_{max} = maximum horizontal length for stable configuration

**$\frac{da}{dt}$ = orbital decay rate



STABILITY LIMITS FOR A "FISH-BONE" CONSTELLATION VS. ORBITAL ALTITUDE

·ASSUMPTIONS

$\ell_2 = \ell_1 = 20$ km

$A_2/m_{12} = 10\ m^2/kg$; $A_1/m_{11} = 4\times10^{-3}\ m^2/kg$

$d_{t2} = 1$ mm (kevlar) ; $d_{t1} = 2$ mm (kevlar)

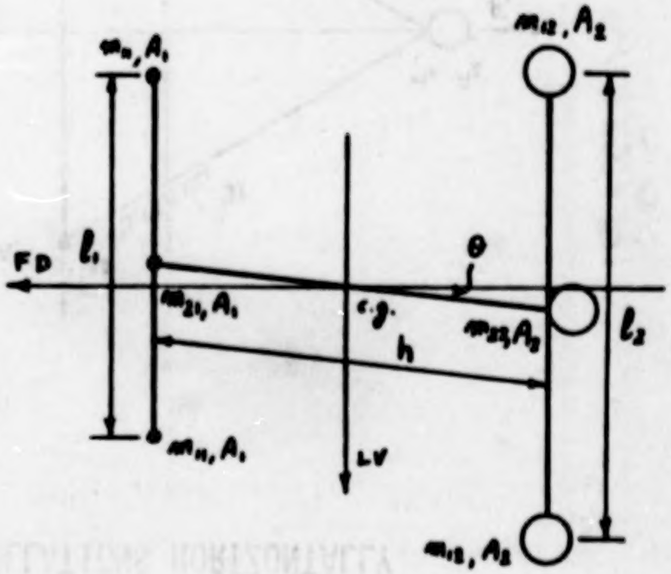
$m_{11} = m_{12} = 200$ kg

$m_{21} = 1000$ kg ; $m_{22} = 800$ kg (deployer) + 200 kg (balloon) = 1000 kg

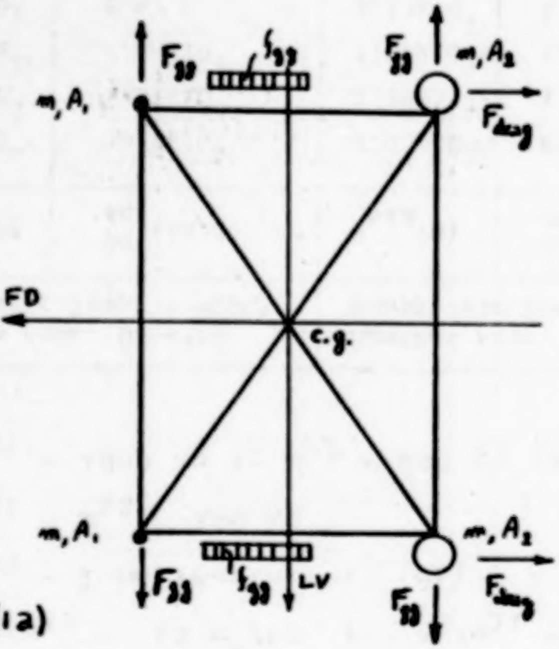
	Minimum Atmo. Density Exospheric Temp. = 600K		Maximum Atmo. Density Exospheric Temp. = 1100K	
z(km)	h_{max}(m)*	$\frac{da}{dt}$ (km/day)**	h_{max}(m)	$\frac{da}{dt}$ (km/day)
150.	9.54×10^4	5.99×10^4	1.33×10^5	8.38×10^4
200.	7.81×10^3	4.83×10^3	1.98×10^4	1.23×10^4
300.	2.26×10^2	1.49×10^2	1.86×10^3	1.13×10^3
400.	1.47×10^1	8.87	3.13×10^2	1.86×10^2
500.	1.50	0.84	6.65×10^1	3.86×10^1

*h_{max} = maximum horizontal length for a stable configuration

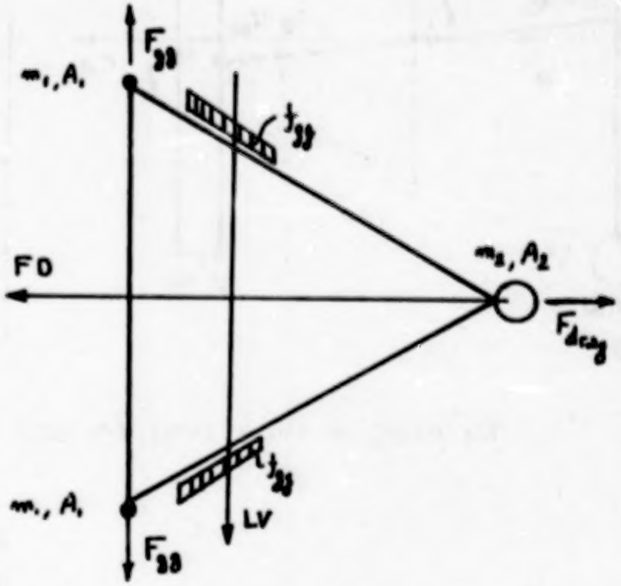
**$\frac{da}{dt}$ = orbital decay rate



·SOME CONCEPTUAL EXAMPLES OF TWO-DIMENSIONAL CONSTELLATIONS HORIZONTALLY STABILIZED BY AIR DRAG (DSC)


F_{gg}
f_{gg}
F_{gg}
m, A_2
m, A_1
F_{drag}
FD
c.g.
m, A_1
m, A_2
F_{gg}
f_{gg}
LV
F_{gg}
F_{drag}

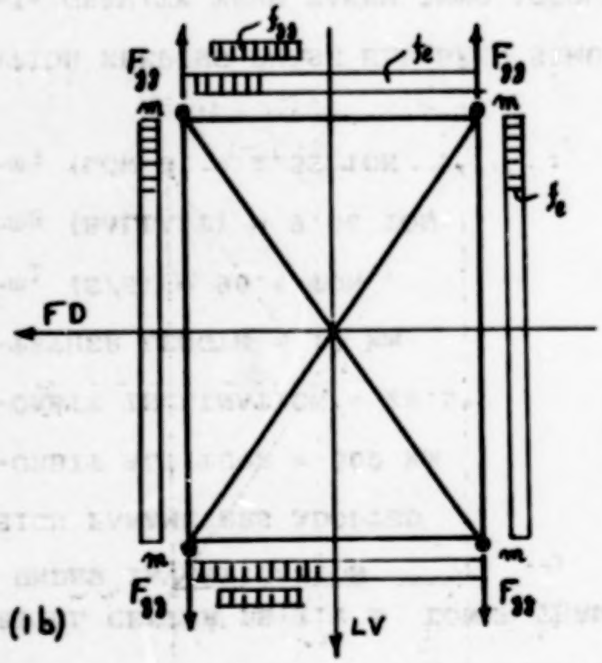
(1a)


F_{gg}
m_1, A_1
f_{gg}
FD
m_2, A_2
F_{drag}
f_{gg}
m_1, A_1
LV
F_{gg}

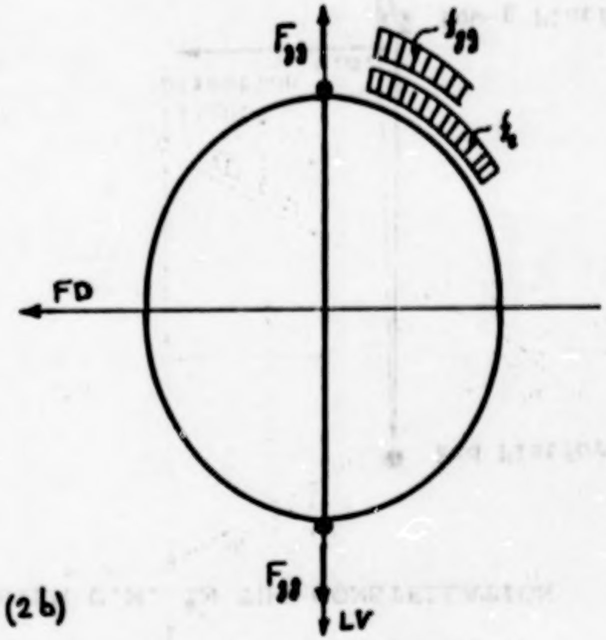
(2a)

-WITH THIS CONFIGURATION THE DRAG FORCE IS FULLY EXPLOITED TO GUARANTEE THE MINIMUM TENSION LEVEL IN THE HORIZONTAL TETHERS AND NOT TO COUNTERACT GRAVITY GRADIENT.

- SOME CONCEPTUAL CONFIGURATIONS OF TWO-DIMENSIONAL CONSTELLATIONS WHERE SHAPE STABILITY IS PROVIDED BY ELECTRODYNAMIC FORCES (ESC)


F_gg
f_gg
f_e
F_gg
m
m
f_e
FD
m
m
F_gg
LV
F_gg

(1b)

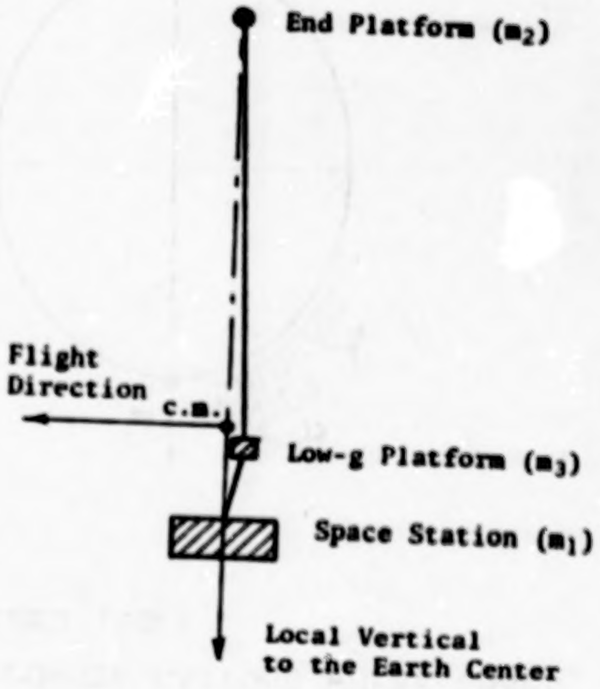

F_gg
f_gg
f_e
FD
F_gg
LV

(2b)

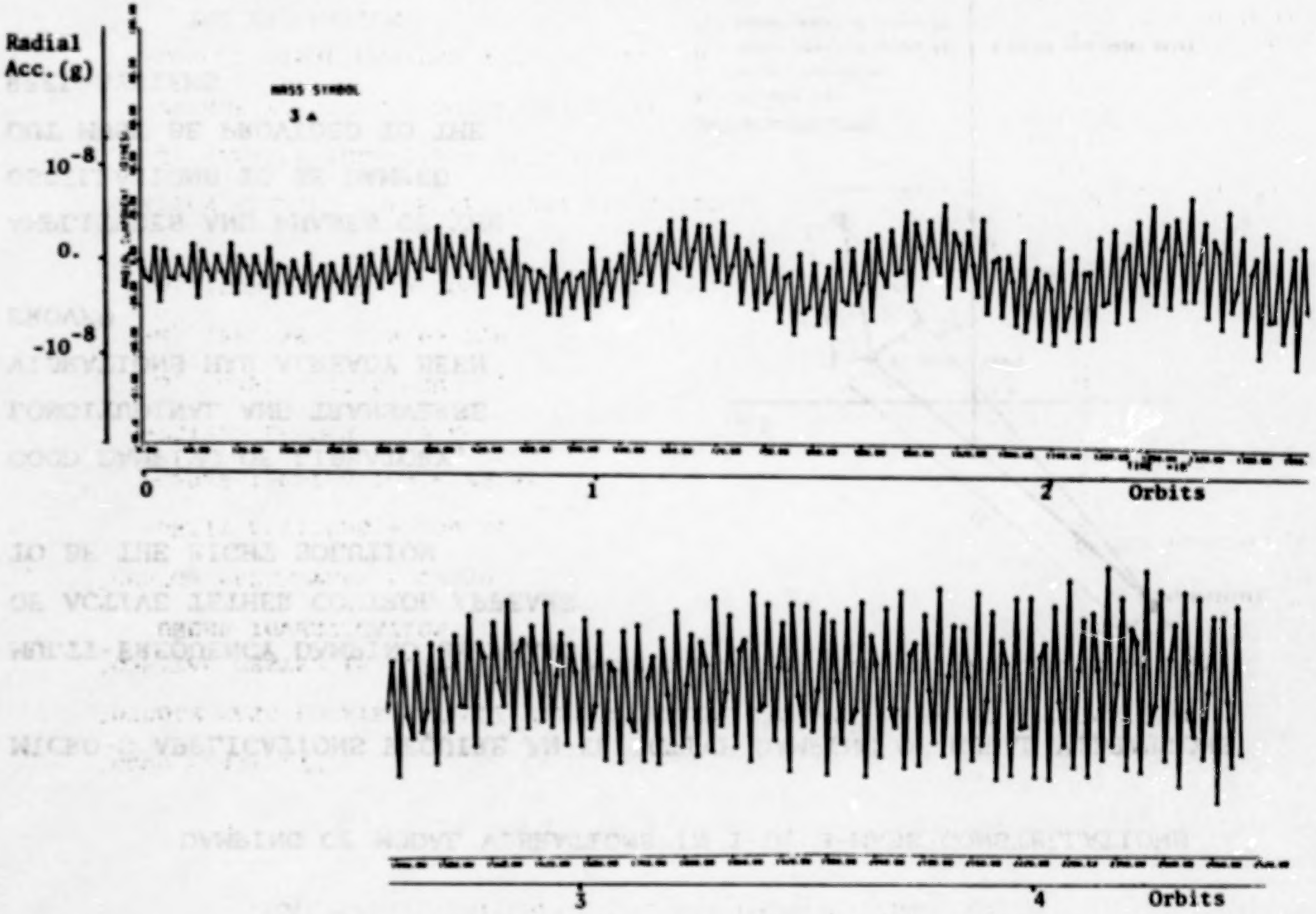
-ELECTRODYNAMIC FORCES STRETCH THE CONSTELLATION WHILE THE RESULTANT IS ZERO SO THAT ORBITAL DECAY IS NOT INCREASED

SINGLE-AXIS, VERTICAL CONSTELLATION WITH THREE MASSES

- GOOD STABILITY
- MIDDLE MASS LOCATED AT THE SYSTEM ORBITAL CENTER FOR LOW-G APPLICATIONS
- ORBITAL CENTER IS 1.2 m LOWER THAN THE SYSTEM C.M. IN THE CONSTELLATION UNDER INVESTIGATION
- DESIGN PARAMETERS ADOPTED
  - ORBIT ALTITUDE = 500 km
  - ORBIT INCLINATION = 28.5°
  - TETHER LENGTH = 10 km
  - m_1 (S/S) = 90.6 TON
  - m_2 (BALLAST) = 9.06 TON
  - m_3 (LOW-G) = 4.53 TON
- STATION KEEPING PHASE HAS BEEN SIMULATED
  - J_2 GRAVITY TERM TAKEN INTO ACCOUNT
  - TETHER TRANSVERSE MODES NEGLECTED
  - LONGITUDINAL DAMPERS NOT INCLUDED IN THE SIMULATION


End Platform (m_2)
Flight Direction
c.m.
Low-g Platform (m_3)
Space Station (m_1)
Local Vertical to the Earth Center

- ACCELERATION LEVEL OF LOW-G PLATFORM PRELIMINARILY ESTIMATED TO BE AROUND 10^{-8}g.
  - -RADIAL COMPONENT, SHOWN IN THE FIGURE, IS THE DOMINATING COMPONENT



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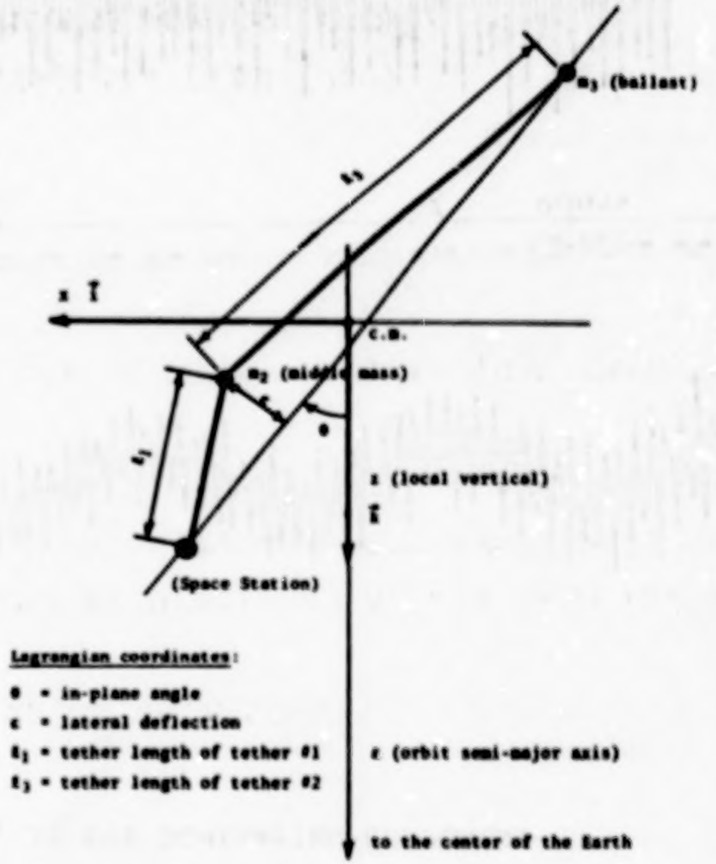
OF POOR QUALITY

- SINGLE-AXIS, VERTICAL CONSTELLATIONS APPEAR PROMISING FOR LOW-G/VARIABLE-G APPLICATIONS
- HIGH FIDELITY ANALYSIS OF EXTERNAL PERTURBATIONS NECESSARY

DAMPING OF MODAL VIBRATIONS IN 1-D, 3-MASS CONSTELLATIONS

- MICRO-G APPLICATIONS REQUIRE AN EFFECTIVE DAMPING OF MODAL VIBRATIONS
- MULTI-FREQUENCY DAMPING BY MEANS OF ACTIVE TETHER CONTROL APPEARS TO BE THE RIGHT SOLUTION
- GOOD DAMPING OF LIBRATORY, LONGITUDINAL AND TRANSVERSE VIBRATIONS HAS ALREADY BEEN PROVED
- AMPLITUDES AND PHASES OF THE OSCILLATIONS TO BE DAMPED OUT MUST BE PROVIDED TO THE REEL-SYSTEMS


m_3 (ballast)
ℓ_2
x
c.m.
m_2 (middle mass)
ε
θ
ℓ_1
z (local vertical)
(Space Station)
r (orbit semi-major axis)
to the center of the Earth

Lagrangian coordinates:

θ = in-plane angle
ε = lateral deflection
ℓ_1 = tether length of tether #1
ℓ_2 = tether length of tether #2

CONCLUSIONS AND RECOMMENDATIONS

- 1-D, HORIZONTAL CONSTELLATIONS STABILIZED BY DIFFERENTIAL AIR DRAG ARE LIMITED BY HIGH ORBITAL DECAY AT LOW ORBITAL ALTITUDES AND SHORT HORIZONTAL LENGTHS AT SS ALTITUDES.

- 2-D, "FISH-BONE" CONSTELLATIONS' STABILITY IS MORE MARGINAL THAN THAT OF 1-D, HORIZONTAL CONSTELLATIONS

- 2-D, ALTERNATIVE CONFIGURATIONS PROPOSED

  - QUADRANGULAR STABILIZED BY DIFFERENTIAL AIR DRAG (DSC)
  - QUADRANGULAR STABILIZED BY ELECTRODYNAMIC FORCES (ESC)
  - PSEUDO ELLIPTICAL STABILIZED BY ELECTRODYNAMIC FORCES
  - TRIANGULAR STABILIZED BY DIFFERENTIAL AIR DRAG
  - QUADRANGULAR DSC OR ESC CAN ACHIEVE STABLE DIMENSIONS OF 10 X 20 KM

    - POWER REQUIRED FOR ESC AND BALLOON DIAMETER FOR DSC PRACTICABLE
    - TRANSIENT DYNAMIC RESPONSE OF THESE COMPLEX STRUCTURES HAS BEEN ONLY PARTIALLY ANALYZED

CONCLUSIONS AND RECOMMENDATIONS - CONTINUED

- 1-D, VERTICAL CONSTELLATIONS ARE PERFECTLY STABLE
  - 3-MASS CONFIGURATION CAN BE CONVENIENTLY USED FOR MICRO-G APPLICATIONS EITHER FROM THE SHUTTLE OR THE SPACE STATION
  - PRELIMINARY EVALUATION OF THE ACHIEVABLE ACCELERATION LEVEL IS AROUND 10^{-8} G. FURTHER STUDIES ARE NECESSARY HOWEVER.
  - MODAL VIBRATION DAMPING BY ACTIVE CONTROL HAS BEEN PROVEN EFFECTIVE
  - 1-D VERTICAL CONSTELLATIONS CAN BE EXTENDED TO MORE THAN 3-MASS IN ORDER TO CREATE A MULTI-PROBE SYSTEM FOR MEASUREMENT OF GEOPHYSICAL GRADIENTS

TETHER DYNAMICS MOVIE

Joe Loftus
NASA/JSC

Joe Loftus presented a film on tethers in space as the final speaker of the day. The film is an animated tutorial which uses computer graphics to illustrate the various uses of tethers and the dynamics of using a tether in space.

The movie is 21 minutes in duration and available in either VHS or 16-mm format. More information may be obtained from:

Robert Brown
Lyndon B. Johnson Space Center
National Aeronautics and Space Administration
Mail Code FM-7
Houston, TX 77058

(713) 483-4751

II

PANEL SUMMARIES AND PRESENTATIONS

SCIENCE APPLICATIONS PANEL

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SCIENCE APPLICATIONS PANEL SUMMARY REPORT

The panel took into consideration two different aspects: those having to do with the very first missions of tethered satellites, and those to be considered for a somewhat far-term future which imply new developments or new technology.

Concerning the near future of TSS, it was clear that the scientific objectives outlined in the Williamsburg workshop and confirmed by the large number of proposals received in response to the TSS announcement of opportunity are essentially well established.

A presentation was made of the scientific experiments to be flown on the TSS-1 mission, which also considered the critical areas to be given special attention from the very beginning. Also, a list of broad areas to be taken into account for the following atmospheric mission was discussed. In general, the panel emphasized the need to consider the integrated character of the payloads which, in turn, requires careful attention to achieve full coverage of science. Understanding the electric and magnetic environment requires tethered satellites (or platforms) to be clean from the standpoint of electric and magnetic contamination to keep undesired noise below the expected level of significant measurements. Understanding the dynamics of the tether and improving atmospheric models are also essential goals, since accurate knowledge in this field is necessary to make possible some of the most interesting applications (among them, studies on gravity and geomagnetic anomalies) near Earth and/or to plan future advanced TSS missions or tether applications to space stations.

In particular, the panel felt appropriate to recommend all possible efforts to:

- o improve the EMC/EMI properties of tethered satellites or platforms
- o improve their DC magnetic cleanliness

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- complement the payload with sensitive, low-power dynamical packages (accelerometer, tensiometers, etc.)
- stimulate close cooperation between dynamicists and aeronomists to get reliable dynamical and atmospheric models

As concerns the low altitude atmospheric missions, the panel discussed the broad areas of interest (listed in table 1) in connection with possible extensions to altitudes below approximately 130 km from the ground. Some possible experiments were presented. P. Dickinson discussed the interest to measure the concentration of atomic oxygen, highly variable in the 90 to 130 km range, by local measurements of resonant fluorescence at 130 nm using a lamp on TSS. (The basic idea is described in the paper by Dickinson et al. entitled "Lower Thermosphere Densities of N_2,O and Ar Under High Latitude Winter Conditions", Appendix 1) D. Cobb discussed a concept of global density mapping of various ionospheric species utilizing bistatic LIDAR, based on triangulated photometric observations from TSS of a fluorescent column excited by a laser on the Shuttle (see the paper by D. McComas et al. entitled "Bistatic LIDAR Experiment Proposed for The Shuttle/Tethered Satellite System Missions", Appendix 2.) Table 2 summarizes the reasons of interest and challenges in the lowered TSS missions.

As concerns possible applications of tethers to space stations, the panel heard the presentation by E. Anselmi on the Science Applications Tethered Platform. Although ideas have been set up by the geophysical and plasma communities, the apparently limited interest by the astronomical community was pointed out. The panel recommends that careful attention be devoted to investigating stability and pointing features of the platform, to check the possibility of using it for astronomical purposes.

The panel also devoted much attention to future scientific applications of tethered satellites. The development of tethered satellite technology offers exciting new possibilities for improved measurements on future solar terrestrial space missions. Tethered satellites suspended from orbiting space vehicles will be an excellent means for studying planetary atmospheres during future survey missions. Instruments at the end of long tethers may be used to collect samples during comet or asteroid rendezous missions.

Concerning remote sensing from space, the concept of stereoscopic observations from tethered platforms for improved cartography has been further developed since the Williamsburg meeting. (See the contributions by S. Vetrella and A. Moccia entitled "High Resolution Remote Sensing Missions of a Tethered Satellite.") Two concepts have been anlayzed. The first involves successive observations along the ground track using a solid-state array detector on a tethered satellite. The second consists of two synthetic aperture radars (SARs) placed vertically on a single tether. Each SAR provides high resolution of surface detail while interferometry between the two SARs gives height information.

Several ideas were discussed concerning future applications of tethers for basic scientific research. These included experimental concepts for testing fundamental physical laws (unified field theories, general relativity), and the development of large aperture telescopes in space for improved astronomical viewing. These ideas are summarized in the contribution by Dr. H. Meyer entitled "Future Applications of Tethers for Basic Scientific Research."

Other contributions to the Science Applications Panel were given by Mr. Tang, describing a technique for analyzing the dynamics of three-dimensional structures using symbolic computer algebra; by Mr. Sciarrino, considering the possibility of experiments on communication links using tethered satellites; by Mr. Purvis, proposing a large "compass in space" to measure the geomagnetic field; and by Mr. Penzo, proposing to place a penetrator at the end of a tether to obtain samples during comet/asteroid rendezvous missions.

TABLE 1

Broad Categories of Experiments for TSS-2

- **Ambient ion and neutral species**
- **Electron, ion temperature and energy balance**
- **Magnetic and gravitational field**
- **Electric field**
- **Electrostatic and electromagnetic waves**
- **Stereoscope remote sensing of the Earth's surface**
- **Dynamics of tethers (and satellites)**
- **"Open wind tunnel" experiments at low altitudes**

NOTE: Important developments are necessary in order for a tethered satellite to be deployed to lower altitudes.

TABLE 2

Measurements Below 130 km

Interest:

- Atmospheric transition from diffusive separation to turbulent mixture of components
- Atomic oxygen to molecular oxygen
- Shuttle and AOTV's major maneuvers occur here
- Higher order terms of gravity and magnetic fields

Challenges:

- Shock waves generated by a vehicle disturb the ambient atmosphere
- Conventional instruments may not work (for example, mass spectrometers)
- Measurement body (i.e., TSS) to be an aerodynamic body
- New techniques to be developed (resonance fluorescence, laser fluorescence, etc.)

NOTE: An aeronomist's noise is an aerodynamicist's data (sometimes vice versa).

Science Applications Panel

Appendix 1

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Lower thermosphere densities of N_2, O and Ar under high latitude winter conditions

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(*Received for publication* 29 *August* 1984)

1. INTRODUCTION

Measurements of the neutral thermosphere made during the Energy Budget Campaign (northern Scandinavia, Nov/Dec 1980) included determinations of N_2, O and Ar densities using rocket-borne experiments. In this paper these results are presented and discussed in the context of other thermospheric observations in the campaign and are compared with a model atmosphere (USSA, 1976).

Because of the lack of photochemical sensitivity of argon and molecular nitrogen, measurement of the ratio of their concentrations in the lower thermosphere has been extensively used as an indicator of the extent to which diffusive separation of atmospheric constituents has occurred. At the altitudes of interest typical time constants for diffusive separation of argon are about 6 days at 100 km and 1 day at 115 km. However, at arctic latitudes, particularly during geomagnetically disturbed conditions, horizontal wind velocities in the lower thermosphere can approach 100 m s^{-1}, while horizontal changes in temperature and composition may be significant over distances of some hundreds of kilometres. Thus the time taken to transport air horizontally to regions with significantly different composition is of the order of an hour. This is short compared with the time constant for (vertical) diffusive separation, at least below about 125 km. Thus at high latitudes the Ar/N_2 ratio is affected by horizontal and vertical winds, as well as molecular and eddy diffusion.

Atomic oxygen is produced throughout the mesosphere and thermosphere, mainly by photodissociation of O_2. Its concentration is also controlled by eddy diffusion loss down into the mesosphere, where its lifetime changes from weeks above 90 km to hours below 80 km. Above the maximum in [O] near 95 km the distribution with height tends towards diffusive equilibrium. Horizontal winds can influence the distribution, especially at high latitudes. However, the lack of photodissociation during polar winter leads to transpolar asymmetry in [O] and an influx of oxygen atoms from the summer hemisphere. This may cause departures from simple diffusive equilibrium distributions in the thermosphere (DICKINSON *et al.*, 1980).

The measurements presented in this paper show striking differences in thermospheric distributions of the neutral constituents under different geomagnetic conditions.

2. EXPERIMENTAL METHODS

The techniques used in this work to measure argon, nitrogen and atomic oxygen densities have been described in detail elsewhere (WIRTH and VON ZAHN, 1981; DICKINSON *et al.*, 1980, 1981). A summary is presented below.

2.1. *Argon and molecular nitrogen*

Rocket-borne mass spectrometers were used to measure the densities of argon and molecular nitrogen (WIRTH and VON ZAHN, 1981). The gas within the instrument was ionised using an electron beam in an ion source. The ions were accelerated into an electrostatic deflector followed by a magnetic deflector to separate the masses. Argon and nitrogen ion currents were measured simultaneously by separate electrometer sensors.

The payloads (E4) were launched at the times shown in Table 1, on Nike-Apache rocket vehicles. An ion getter pump was used to evacuate the instrument before launch. At 64 s after launch (59 km nominal altitude) the payload was separated from the rocket motor. During the remainder of the ascent gas releases within the instrument provided calibration signals, and a titanium sublimation pump was used to restore the vacuum. Shortly before apogee (125 km nominal altitude) the ion source cover was removed to allow ambient gas into the instrument. A downward pointing attitude for the orifice permitted good gas collection efficiency during the descent. The instrument sensitivity was constant down to about 100 km (by which height the gas influx had raised the pressure in the instrument enough to cause some loss of sensitivity). The collection efficiency was a function of mass, relative velocity and angle of attack of the incoming gas. The results were corrected for these factors, although the limited accuracy of attitude reconstruction means that the attitude dependence may not have been completely removed.

The experiment provided argon and molecular nitrogen densities between 95 and 125 km with a spatial resolution of < 100 m. Furthermore, from these results height profiles of the temperature could be deduced.

2.2. *Atomic oxygen*

The concentration of ground state O (^3P) oxygen atoms [O] was measured using rocket-borne UV resonance lamps. Two types of payload (E5 and E10) were used, on Petrel II and Taurus-Orion rocket vehicles, respectively. On the E5 payloads measurements were made of resonance fluorescence and absorption using the OI ($^3P_J - {}^3S_1$) triplet at 130 mm (DICKINSON *et al.*, 1980). The experiment on the E10 payload measured resonance fluorescence alone, using a lamp emitting the same triplet (HOWLETT *et al.*, 1980). The flight details are included in Table 1.

The lamps for the E5 payloads were calibrated before flight by measuring absorption in known atomic oxygen concentrations in a laboratory flowing afterglow. The absorption measurements on the rocket were over a path length of 40 cm perpendicular to the rocket axis using a deployed mirror. The experiment provided absolute values for [O] at concentrations above about 10^{10} cm^{-3}. The resonance fluorescence was normalised to the absorption values using a smoothed conversion curve linearly extrapolated to low concentrations. This method can measure concentrations as low as 2×10^{-7} cm^{-3} with a height resolution of 0.5 km and a precision (standard deviation) of ±100%. This limit may be adversely affected by background signals due to aurorae or airglow. Lower concentrations may be detectable with reduced height resolution.

For the experiment on E10 the resonance fluorescence signal was converted to absolute values of [O] using measured photon fluxes and efficiencies of the lamp, sensor and viewing geometry. Allowance was made for the non-linear response of the resonance fluorescence experiment at high values of [O].

The resonance lamps were modulated in intensity with a 50% on–off duty cycle at 200 Hz to allow the resonance fluorescence signal from ambient [O] to be differentiated from background due to airglow and auroral emissions at 130 nm. On E5 the signals were sampled at 800 Hz, giving two measurements with the lamp on and two with it off per modulation cycle. The lamp emitted a weak afterglow during the first sample with the lamp 'off'. This gave rise to weak resonance fluorescence signals which could be found by subtraction of the following sample, which contained background only. The afterglow fluorescence was normally a constant proportion (near 5%) of the fluorescence with the lamp on. For part of one flight the full fluorescence plus background signal was saturating the counter electronics (in an aurora), but the afterglow plus background was not doing so. It was then possible

Table 1. Flight details

		Payload type	E4	E10	E5
		Constituents measured	[Ar][N$_2$]	[O]	[O]
		Launch site	Andøya	Andøya	Kiruna
		Group	Bonn	Utah	RAL/UCW
Salvo	Date	Conditions	Launch times		
C	11 Nov. 80	Quiet	00:12:00		00:12:00
B	16 Nov. 80	Mod. disturbance	03:31:00	03:16:00	
A2	30 Nov. 80	Strong disturbance			23:45:30

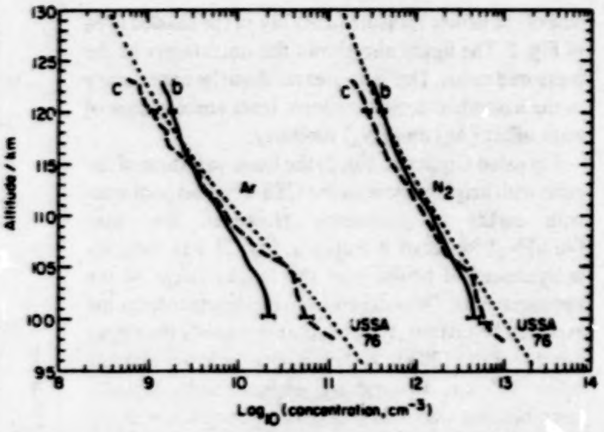

Fig. 1. Argon and nitrogen concentration (left and right, respectively). Measured by Bonn University Mass Spectrometers. b, Salvo B, moderately disturbed night; c, salvo C, quiet night; USSA 76, U.S. Standard Atmosphere. Flight details in Table 1. Uncertainties in the measured concentrations are ±10% and ±20% at 120 km and 100 km, respectively.

to use the afterglow data to fill in the lost data from the full fluorescence. A substantial part of the aurorally disturbed data was recovered in this way. The signals on the other two flights did not saturate.

From these measurements three atomic oxygen profiles have been derived. These are described in Section 3.2.

3. MEASUREMENTS

3.1. [*Ar*], [N_2] *and gas temperature results*

The mass spectrometer measurements of argon and nitrogen concentrations are shown in Fig. 1 for salvoes B and C. The error bars indicate the uncertainty in the absolute values of the concentrations ('accuracy'). The statistical errors ('precision') were too small to show. Also shown are the values given in the United States Standard Atmosphere (USSA, 1976) for the concentrations of these constituents.

In salvo C (curves c, Fig. 1) both constituents were close to 70% of the USSA 76 values over the height range of the measurements (100–125 km) except for perturbations below about 105 km, which may arise in part from imperfections in vehicle attitude reconstruction. The latter uncertainty is included in the error bars at 100 km.

By contrast, the results from salvo B (curves b, Fig. 1) show that the slope of the [N_2] profile differed from USSA 76 in having greater scale heights and higher derived gas temperatures. An even greater departure from the USSA 76 occurred in the [Ar] profile.

The height variation of the concentration ratio [Ar]/[N_2] is shown in Fig. 2 for salvoes B and C. Also shown are values derived from the USSA 76 and the upper and lower quartiles (labelled 3/4 and 1/4, respectively) of the range of earlier measurements by similar rocket-borne techniques [PHILBRICK *et al.*, 1974, 1978; TRINKS *et al.*, 1978; KENESHEA *et al.*, 1979; OFFERMANN *et al.*, 1981 (review)]. Thus at each height

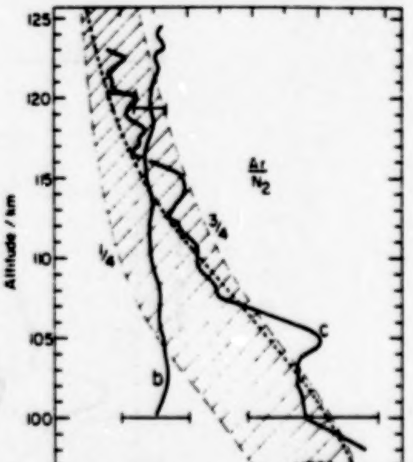

Fig. 2. Argon nitrogen concentration ratios. b, Salvo B; c, salvo C; USSA 76, U.S. Standard Atmosphere. Shaded area includes 2nd and 3rd quartiles of earlier measurements (see text). Uncertainties in the measured ratios are ±10% and ±20% at 120 km and 100 km, respectively.

half of the earlier measurements lay in the shaded area of Fig. 2. The figure also shows the uncertainty in the measured ratios. This is no greater than the uncertainty in the individual concentrations, since some causes of error affect [Ar] and [N_2] similarly.

For salvo C (curve c, Fig. 2) the basic variation of the ratio with height is close to the USSA 76 and conforms with earlier measurements. However, the ratio [Ar]/[N_2] for salvo B (curve b, Fig. 2) was virtually independent of height over the height range of the measurements. This is a substantial departure from the expected behaviour. In particular it exceeds the upper quartile above 120 km yet falls below the lower quartile below 105 km. In contrast, earlier results broadly resembled the USSA 76 in height dependence, with the flight to flight variability being attributable largely to displacement of the curve in height (i.e. changes in the height of the turbopause). So although the salvo B profile spans the range of earlier results and is unexceptional at any given height, its height variation is much smaller than has been observed before.

The gas temperatures shown in Fig. 3 were deduced from the [N_2] profiles by integration downward along the profile, assuming hydrostatic equilibrium and an initial value for the gas temperature at 123 km on the profile. For each salvo the analysis was performed for three initial values of temperature. The dependence of the deduced temperatures upon the initial value is seen to diminish as the integration progresses downwards. The temperatures given in the USSA 76 are also shown. The salvo C results indicate temperatures in broad agreement with the USSA 76. The salvo B results suggest that there was a temperature enhancement of 40–60K at altitudes up to at least 118 km on that occasion.

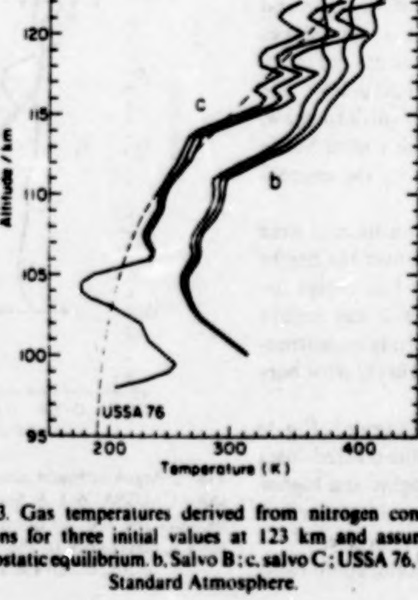

Fig. 3. Gas temperatures derived from nitrogen concentrations for three initial values at 123 km and assuming hydrostatic equilibrium. b, Salvo B ; c, salvo C ; USSA 76, U.S. Standard Atmosphere.

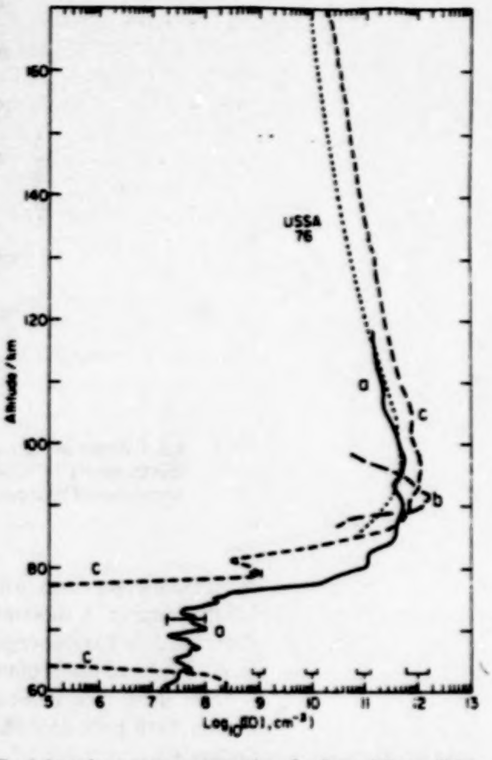

Fig. 4. Atomic oxygen concentrations for three nights. a, Salvo A2, very disturbed night ; b, salvo B ; c, salvo C. Measured by resonance fluorescence at 130 nm [Utah State University, (b)] and by resonance fluorescence and absorption [RAL/UCW (a, c)]. USSA 76, U.S. Standard Atmosphere. Statistical error bars shown on curves a and c. Absolute scale uncertainty shown above concentration axis.

3.2. [*O*] *results*

In Fig. 4 the three measurements of atomic oxygen are compared with the USSA 76 values. The standard deviations arising from random variations in the resonance fluorescence counts are indicated on the curves. At concentrations above about $10^{10}\,\mathrm{cm}^{-3}$ these were too small to show. Uncertainty in the absolute scale is indicated above the concentration axis. This became greater at high concentrations due to the non-linear responses of the experiments. The results for the geomagnetically quiet day, salvo C (curve c), covered the height range 60–170 km. Down to 120 km the concentrations were about 2.5 × USSA 76 values. The scale height was about 22 km, varying less with altitude than the USSA 76 values do. Some structure was evident below about 110 km and the local 'scale height' minima were about 10 km. At 96 km the peak concentration of atomic oxygen was 1.1×10^{12} cm^{-3}, as measured by the absorption experiment. Below a small layer with 10^{9} cm^{-3} at 79 km the cut-off of the layer occurred at 77.5 km, to concentrations below 10^{5} cm^{-3}. There was evidence of a region with [O] up to 10^{8} cm^{-3} below 64 km from both ascent and descent data from the resonance fluorescence experiment.

For the moderately disturbed night, salvo B (curve b, Fig. 4), the atomic oxygen results cover the altitude range 86–98 km. At greater altitudes the high background signal due to aurorae and airglow raised the threshold for detection of resonance fluorescence signals. For that reason the absence of data above 98 km does not mean that no atomic oxygen was present. Thus the observed 'scale height' of 2 km near 95 km could have been due to local structure in the profile and should not be extrapolated to greater heights. The peak concentration deduced from the resonance fluorescence experiment was 1.4×10^{12} cm^{-3} at 92 km. The lowest concentration detected by this experiment was 3×10^{10} cm^{-3} at 86 km. This concentration was encountered at 84.5 km in salvo C and 79 km in salvo A2 (curve a), illustrating the flight to flight variability in the height below which the [O] layer cuts off. The topside result for salvo B is radically different from the other profiles, and indeed from previous measurements and models of atomic oxygen profiles. Possible causes within the experiment have been examined. In particular, the large background signals detected on this flight did not saturate the counter or cut off the resonance fluorescence signals. It is concluded that the results shown represent the actual [O] profile up to 98 km.

The results for the day with very disturbed geomagnetic conditions, salvo A2 (curve a), cover the altitude range from 60 to near 120 km (see Fig. 4). Intense auroral background emissions during this flight prevented measurements above 120 km due to saturation of the counting electronics. Above 95 km the [O] values straddle the USSA 76 and at 97 km a peak value of 5×10^{11} cm^{-3} was measured by the absorption experiment. At 90 km a second peak of similar concentration was observed, exceeding the USSA 76 by a factor of 2. Below 87 km the observed concentrations were greater than in salvo C and cut off 6 km lower. A weak concentration of 2×10^{7}–10^{8} cm^{-3} was observed by the resonance fluorescence experiment between 76 and 60 km.

4. DISCUSSION

4.1. *Salvo C*

On the quiet day (salvo C) the atmospheric neutral constituents showed little departure from normal behaviour. The thermospheric temperatures deduced from the N_2 profile were close to the nominal USSA 76 values up to 115 km, above which they increased rather more slowly with height.

The atomic oxygen profile from salvo C shows a slightly larger scale height than is expected under diffusive equilibrium at 120 km. This is similar to earlier measurements in northern hemisphere winter (Dickinson *et al.*, 1980) which are consistent with the assumption of a net downward flux of oxygen atoms at that time. Hence the larger scale heights should not be taken to indicate higher thermospheric temperatures than given by the USSA 76 or by the [N_2] scale heights during the same quiet day salvo. The structure in the atomic oxygen profile below 110 km was similar in the ascent and descent measurements and is therefore interpreted as normal horizontal stratification associated with atmospheric dynamics. One cause of this could be layered turbulence, giving rise to well mixed layers within which [O] 'scale heights' approach the total density scale height (e.g. 96–101 km, 88–91 km and 79–81 km). Another possible cause of the structure could be wind shears causing arrival of air masses at different heights from different locations and having different atomic oxygen contents determined by their respective photochemical histories. Structure might also arise from density/temperature fluctuations in gravity waves. The occurrence of similar structures at 100–115 km in [O], [N_2] and [Ar] is probably not significant, since the [O] measurement was at Kiruna and the others at Andøya. It is therefore difficult on this evidence alone to differentiate between the above mechanisms to account for the structure in [O].

4.2. *Salvo A2*

The atomic oxygen measurements (Fig. 4) show striking differences. Comparing the results from the quiet and very disturbed nights (curves c and a, respectively), the differences are as expected if a significant increase in eddy diffusion loss of oxygen atoms occurred on the disturbed night.

The reduced altitude of the atomic oxygen cut-off on the disturbed night means that there was a higher atom concentration in the region of rapid loss by three body recombination. The associated downward flux depleted the peak and topside of the layer and resulted in a change in total (column) content of oxygen atoms by a factor of two by comparison with the quiet night.

The enhanced concentrations at altitudes between 80 and 65 km on the disturbed night may be attributable to the production of oxygen atoms by high energy auroral particles dissociating O_2. The observed concentrations at these low altitudes are about 1% of the normal daytime values caused by solar photodissociation, but significantly higher than the minimum measureable concentration in the experiment (about 10^7 cm^{-3}).

4.3. *Salvo B*

On the geomagnetically moderately disturbed day (salvo B) the neutral constituents showed marked departures from normal behaviour. The thermospheric temperature deduced from the N_2 profile was 50 ± 10K higher than the USSA 76 at 110 km. As described in Section 3.1, the $[Ar]/[N_2]$ ratio was virtually constant throughout the height range observed (100–125 km), showing that on this occasion this part of the atmosphere was well mixed. The mixing ratio of 0.5% was less than half of the value in the lower atmosphere (1.2%). In addition, we note that the water vapor mixing ratio was comparatively high (about 10 ppm) and nearly constant throughout the altitude region 85–100 km (Grossmann *et al.*, 1985).

Mixing a standard atmosphere between 100 and 125 km would produce an Ar/N_2 mixing ratio of 0.84% and an increase in the upper bound of the mixed region cannot bring the ratio down below about 0.8%, as the mass of gas involved becomes small. Hence to produce the observed ratio of 0.5% requires net downward transport to displace the relatively argon-rich gas at lower altitudes. This downward transport was accompanied by a thorough mixing process, as indicated by the ratio Ar/N_2 being nearly constant over a 20 km altitude range. Both processes, downward bulk motion and large scale mixing, could well have been effected by a mesoscale meridional circulation cell including strong wind shears. Vigorous southward winds were measured above 100 km during salvo B at Kiruna by both an instrumented falling sphere experiment and a vapor release (Rees *et al.*, 1985).

The southward component was more than 100 m s^{-1} at 120 km altitude and even stronger higher up. On the other hand, the data collected during the salvo B of the Energy Budget Campaign does not allow us to establish the details of this circulation pattern.

Zonally averaged models of thermospheric dynamics (e.g. Roble and Kasting, 1984) have limited spatial and temporal resolution and cannot be expected to provide a sufficiently detailed prediction of thermospheric behaviour for use as an input in analysing particular events such as are reported here, particularly when the measurements were taken in close proximity to the auroral oval.

The measurement of atomic oxygen at Andøya in salvo B (curve b, Fig. 4) is highly untypical. The large peak concentration and the layer bottom above the other measurements imply, by extension of the arguments used in Section 4.1 that there was little downward transport of atoms by eddy diffusion below the layer peak at 90 km. This is not inconsistent with the gross downward flux implied above from the Ar/N_2 results at higher altitudes for this night, since eddy diffusion transport requires no bulk movement and vice versa. The steep topside of the atomic oxygen layer is very difficult to explain. Bulk downward transport could not provide '[O] depleted' air, since the typical mixing ratio $[O]/[N_2]$ increases with altitude. It is possible that the effect is an extreme example of the local structuring normally seen in [O] profiles and that the distribution at greater altitudes was more typical, but not detected due to the intense auroral background emissions.

In view of the problem in interpreting the [O] profile from salvo B it is interesting to note some qualitative similarities between the observed atomic oxygen concentrations (Fig. 4) and the predictions of Roble and Kasting (1984) for 69°N (Fig. 5). They considered three cases: solar heating only; solar heating plus high latitude heating; solar heating plus three times as much high latitude heating. Profiles interpolated from their contour figures 3b, 5b and 7b are shown in this paper in Fig. 5, labelled C, A and B, respectively, to facilitate comparison with the observations in Fig. 4.

The points of similarity are as follows. Firstly, the moderate high latitude heating decreased the modelled concentration by about a factor of two from the layer peak upwards. It did not affect the scale height in the thermosphere. This is closely similar to the relationship between the measurements in salvoes C and A2. Secondly, the model with stronger heating predicted a severe depletion in the thermospheric concentration (a factor of 10 at 150 km in the model) associated with a marked reduction in thermospheric scale height by about a factor of 2 up to 150 km (Fig. 5, curve B). From this we may imply that dynamical/chemical effects can cause changes in the lower thermosphere which are qualitatively similar to the observations in salvo B (Fig. 4, curve b). The measured high latitude heating on that occasion did not exceed that seen during salvo A2 (Baumjohann *et al.*, 1984). However, the location of the heat input was overhead for salvo B but somewhat further south for salvo A2, while the measurements were made later at night for salvo B (see Table 1). Such detailed differences on the two occasions may have resulted in differing locations for the boundary between the solar-driven and high latitude circulations. To the north of this boundary the vertical winds are upward

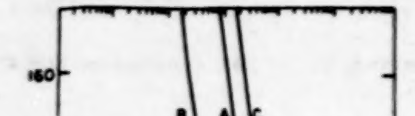

Fig. 5. Model profiles of atomic oxygen concentration for 69°N (winter) interpolated from zonally averaged chemical-dynamical model of Roble and Kasting (1984). C, solar heating only; A, solar and high latitude heating; B, solar and 3 × high latitude heating.

and to the south they are downward [the predicted location of this boundary, particularly below 150 km, depends upon what model is used (cf. Roble and Kasting, 1984; Roble *et al.*, 1977)]. For these reasons the points of similarity between the observations and the predictions of Roble and Kasting (1984) are not thought to contradict the conclusion from the argon depletion in salvo B that a downwind had been occurring on that occasion.

CONCLUSIONS

Measurements of neutral atmospheric constituents during the Energy Budget Campaign show that under quiet geomagnetic conditions there was reasonable agreement with the United States Standard Atmosphere (USSA 76). [N_2] and [Ar] were about 70% of the predicted values and [O] about 2.5 times greater. During a night with moderate geomagnetic disturbance, and substantial accumulated Joule heating from auroral activity, there were striking departures from the USSA 76. These included a constant Ar/N_2 mixing ratio of 0.5% from 100 to 125 km. To explain this a downward bulk movement combined with large scale mixing in the thermosphere is invoked. Increased values of gas temperatures were derived from the N_2 profile and also an unusually narrow layer of atomic oxygen was detected.

On a more strongly disturbed night an atomic oxygen profile showed half the column content observed on the quiet night, lower peak concentration and increased concentration at lower altitudes. These effects are consistent with enhanced eddy diffusion loss during the auroral activity.

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REFERENCES

Baumjohann W., Gustafsson G., Nielsen E., Ranta H. and Evans D. S. 1985 *J. atmos. terr. Phys.* **47**, 27.
Dickinson P. H. G., Bain W. C., Thomas L., Williams E. R., Jenkins D. B. and Twiddy N. D. 1980 *Proc. R. Soc.* **A369**, 379.
Dickinson P. H. G., Williams E. R. and Jenkins D. B. 1981 *Energy Budget Campaign 1980: Experiment summary*, Offermann D. and Thrane E. V. Eds, p. 340. BMFT-FB-W-81-052, Bundesministerium für Forschung und Technologie, Bonn, F.R.G.
Grossmann K. U., Frings W. G., Offermann D., André L., Kopp E. and Krankowsky D. 1985 *J. atmos. terr. Phys.* **47**, 291.
Howlett L. C., Baker K. D., Megill L. R., Shaw A. W., Pendleton W. R. and Ulwick J. C. 1980 *J. geophys. Res.* **85**, 1291.
Keneshea T. J., Zimmerman S. P. and Philbrick C. R. 1979 *Planet. Space Sci.* **27**, 385.
Offermann D., Friedrich V., Ross P. and von Zahn U. 1981 *Planet. Space Sci.* **29**, 747.

Philbrick C. R., Golomb D., Zimmerman S. P., Keneshea T. J., McLeod M., Good R. D., Dandekar B. S. and Reinisch B. W. 1974 *Space Res.* **14**, 89.

Philbrick C. R., Schmidlin F. J., Grossmann K. U., Lange G., Offermann D., Baker K. D., Krankowsky D. and von Zahn U. 1985 *J. atmos. terr. Phys.* **47**, 159.

Rees D., Charleton P., Carlson M. and Rounce P. 1985 *J. atmos. terr. Phys.* **47**, 195.

Roble R. G., Dickinson R. E. and Ridley E. C. 1977 *J. geophys. Res.* **82**, 5493.

Roble R. G. and Kasting J. F. 1984 *J. geophys. Res.* **89**, 1711.

Trinks H., Offermann D., von Zahn U. and Steinhauer C. 1978 *J. geophys. Res.* **83**, 2169.

USSA 1976 *United States Standard Atmosphere*. U.S. Govt. Printing Office, Washington DC.

Wirth J. and von Zahn U. 1981 *Energy Budget Campaign 1980: Experiment summary*, Offermann D. and Thrane E. V. Eds, p. 310. BMFT-FB-W-81-052, Bundesministerium für Forschung und Technologie, Bonn, F.R.G.

Science Applications Panel

Appendix 2

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Bistatic LIDAR experiment proposed for the shuttle/tethered satellite system missions

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A new experiment concept has been proposed for the shuttle/tethered satellite system missions, which can provide high-resolution, global density mappings of certain ionospheric species. The technique utilizes bistatic LIDAR to take advantage of the unique dual platform configuration offered by these missions. A tuned, shuttle-based laser is used to excite a column of the atmosphere adjacent to the tethered satellite, while triangulating photometric detectors on the satellite are employed to measure the fluorescence from sections of the column. The fluorescent intensity at the detectors is increased about six decades over both ground-based and monostatic shuttle-based LIDAR sounding of the same region. In addition, the orbital motion of the shuttle provides for quasiglobal mapping unattainable with ground-based observations. Since this technique provides such vastly improved resolution on a synoptic scale, many important middle atmospheric studies, heretofore untenable, may soon be addressed.

INTRODUCTION

Remote LIDAR measurements of ionospheric species have been successfully made from the ground and from aircraft. The technique involving resonance scattering was first carried out for sodium in the 90-km layer shortly after the development of the tunable dye laser.[1] With improvements in laser/LIDAR technology, the ground-based observations were extended to other species such as potassium[2] and to phenomena such as wave structures in the upper atmosphere.[3] The recent University of Illinois/Goddard SFC work[4] demonstrates that these observations can also be made from aircraft and opens the way towards a general class of ionospheric LIDAR measurements that can be made from moving platforms. In the limit of orbiting platforms, such as the shuttle, this affords the attractive prospect of global coverage and a much more comprehensive view of the behavior of many physical processes in the ionosphere. NASA's shuttle LIDAR report[5] examines many such studies and features LIDAR profiling of sodium as one of the early, desirable targets.

During the late 1980's, NASA will fly a series of missions involving the space shuttle with a tethered satellite system (TSS)[6]; thereby creating dual-platform observing configurations with the tethered satellite (TS) and the shuttle. A new experiment concept, suggested by McComas and Spence,[7] which takes advantage of this unique configuration, has recently been proposed[8] in response to NASA's TSS announcement of opportunity. The experiment, if accepted, will provide global high-resolution density profiles of certain ionospheric species. The technique, laser induced fluorescence (LIF), utilizes a bistatic LIDAR configuration to provide triangulated photometric observations from the tethered satellite of a fluorescent column excited by a laser on the shuttle. Figure 1 illustrates the LIF experiment configuration. This method has advantages over both ground-based monostatic LIDAR and over shuttle-based, downward looking LIDAR, the major advantage being that the excited region under study is much closer to the detectors, giving a vastly improved signal-to-noise ratio. During TSS "tether-down" missions, the high-resolution global density profiles obtained by the LIF technique will be extremely valuable for the development of more detailed understanding of middle atmospheric physics.

I. THE EXPERIMENTAL CONCEPT

The TS system in the tether-down mode places the shuttle at ~200-km altitude with the TS in the ~100 to 150-km altitude regime. This region has not been experimentally sampled in detail, since it is too high for balloons and too low for long-lived satellites. Currently our knowledge about this region has been acquired from limited and often ambiguous observations made by short duration sounding rocket traversals, ground-based remote sensors (airglow photometry and LIDAR), and from the results of ionospheric modeling. The LIF technique, invented to take full advantage of the unique dual platform configuration offered by the TSS missions, is capable of providing data with accuracies heretofore unattainable, in this altitude region. By this method, high precision, global density measurements of various ionic and neutral species can be made. Shuttle-based lasers can be tuned to a particular resonant frequency to excite specific

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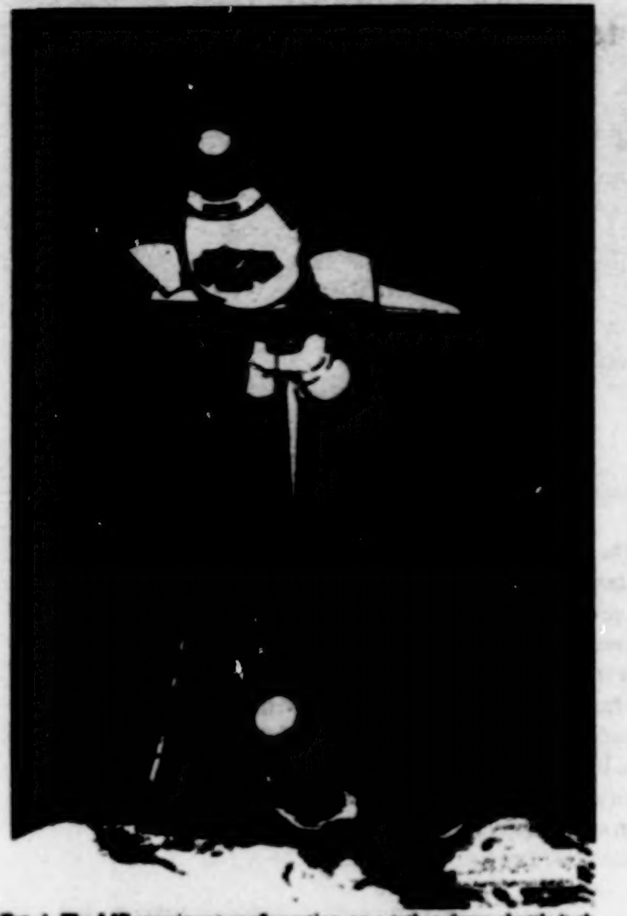

FIG. 1. The LIF experiment configuration on a tether-down shuttle/tethered satellite system mission. A tunable laser on the shuttle excites a column of the atmosphere adjacent to the tethered satellite. Fluorescence from various sections of the column is measured with photometers situated on the nearby tethered satellite.

species within a column of the ionosphere adjacent to the TS. Induced fluorescence from different altitude bands along this column is then observed on the TS by an array of photometers sensitive to the fluorescence. By accurately knowing the location of the TS with respect to the excitation beam, the returned signals can be used to derive concentration profiles.

While the LIF experiment configuration essentially constitutes a bistatic LIDAR, it has numerous advantages over ground-based and shuttle-only-based monostatic LIDAR. The configuration of the TSS missions allows detectors to be located very close to the region that is being probed. The irradiance seen at a detector drops off approximately as the inverse square of the distance from the fluorescent region, and the proximity of the excited region to the detector is, therefore, a major factor in the signal magnitude observed at the detector. For the LIF configuration the path length between the excited region and the detector is ~100 m, while the path length for either ground- or shuttle-based LIDAR is ~100 km; the intensity at the detector is, therefore, ~10^6 times greater. Ground-based LIDAR has the additional problem that optical paths must extend through the troposphere where substantial extinction occurs at many wavelengths. Similarly, in the sun-lit hemisphere, shuttle-based monostatic LIDAR must measure backscattered returns from these regions against the bright tropospheric background. In contrast to these techniques, the LIF method guarantees the observation of nearby regions as well as excluding optical paths that include high background and extinction regions.

II. INSTRUMENTATION

The LIF technique may be applied to many ionospheric species, both neutral and ionic. The applicability of the technique to a wide variety of investigations necessarily precludes a single description for all possible LIF instrumentation and hardware. Instead, a general description of the technique is more appropriate to encompass presently envisioned LIF experiments. The LIF experiment configuration (see Fig. 1) would utilize a tunable pulsed laser onboard the shuttle to excite fluorescence of an atmospheric species along the conical laser-beam path directed to a position ~100 m from the TS. The choice of laser would depend primarily upon the trace species to be investigated, the resonant and fluorescent wavelengths that are available for that species, and the ability of a laser to emit at one of these wavelengths.

By choosing to illuminate a region near the TS-mounted detectors, as opposed to relying upon long path length backscatter, the very large return signal strength provided by this experiment configuration makes it feasible to utilize numerous wavelengths with smaller absorption cross sections. While present laser technology makes it impossible to access many of the large absorption cross-section wavelengths, conventional lasers are suitable to access some with smaller cross sections. Consequently, certain species inaccessible to present LIDAR experiments may now be observed. In addition, it is possible to use lower power lasers than are required for monostatic shuttle-based LIDAR. The advantages of this are multifold, namely longer laser lifetime, narrower linewidths, easier tunability, smaller size, lower power requirements, easier production of a high repetition rate, and lower cost.

Regardless of species choice, a precision spectrometer, or the optogalvanic effect[9] in a hollow cathode lamp, will be used to automatically maintain overlap of the laser wavelength with the chosen fluorescent line. Wavelength tuning of the laser line (accurate to 10%–20% of the laser linewidth) will correct for the Doppler shift of the line due to the orbital motion of the shuttle. The perceived shift is proportional to the orbital velocity (~7 km/s) over the speed of light, times the sine of the small angle between the shuttle TS separation vector and nadir. For the maximum envisioned angle of ~5°, the shift amounts to ~ ± 0.012 Å, which is of the order of visual, ionospheric Doppler linewidths.

An array of photometers, mounted at various polar angles on the TS, will sample the signal returned from the nearby fluorescent region. These photometers will have aperture areas ~10 cm^2, focal lengths of 5–8 cm (~$f/2$), and a variety of fields of view (~7×10^2 sr). Each photomultiplier detector will have an interference filter wheel to allow for selective observation at specific wavelengths. With this array induced fluorescence will be measurable, as well as passive photometry of natural airglow and TS-induced heating emissions.

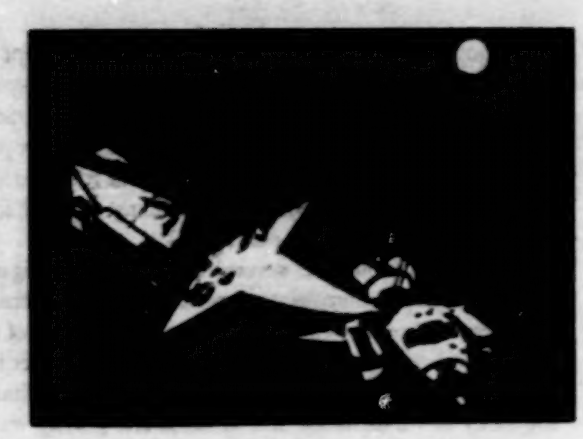

FIG. 2. The laser directional ranger (LDR) subsystem provides the precise tethered satellite locational information required to point the LIF excitation laser and reduce the photometer data.

An additional and important supporting component of this system is a subsystem for locating the TS and for differential pointing of the LIF laser. This laser directional ranger (LDR) subsystem provides a means for the accurate location and ranging of the TS with respect to the shuttle. Such a system not only assures the proper coordinated pointing required, but also ultimately yields the fluorescent region to TS separation necessary for the conversion of LIF measured signals to actual species densities. The basic LDR technique calls for the timing of a laser beam directionally pulsed from the shuttle to the TS and reflected back. By utilizing modern laser and optical techniques, the TS can be located to within ~10 m horizontally at a 100-km distance from the shuttle, while the range is found to within only a few centimeters. The LDR subsystem (see Fig. 2) consists of five integrated components; corner-cube reflector, laser source, photometric detector, tracking mirror system, and instrument electronics and microprocessor.

A passive lightweight corner-cube reflector mounted on the shuttle side of the TS will perform the requisite reflection of the laser pulses. Corner-cube reflectors have the essential property that any reflected beam path is always parallel to the incident beam path. On the shuttle, a 1.06-μm neodymium YAG laser capable of delivering ~2 mJ/pulse at repetition rates up to ~100 Hz, will supply the necessary pulsed beam source. Analysis indicates that a pulse duration of ~10 ns and a beam divergence angle of ~1 mrad will provide ample signal over background levels for this application and will yield a beam well within ANSI eye safety criteria for ground-based observers.

The reflected beam detecting photometer, also on the shuttle, will consist of a 100-cm^2 aperture telescope and a silicon avalanche quadrant detector with an ~10-Å passband filter at 1.06 μm. The field of view will be 1–4 mrad and the system focal length ~25 cm (~$f/2.2$) for a quadrant detector chip diameter of ~0.1 cm. Using this detected signal, the reflected image in the system field of view can be automatically adjusted with a tracking mirror system to continuously determine the TS location and precisely point the laser/detector mirror assembly along a parallel axis. The mirror pointing system consists of a mirror, optically flat to $\sim\frac{1}{4}$ wavelength, which can be pointed repeatedly to within 0.1 mrad and incrementally by 0.03 mrad.

Associated logic and electronics will control the coordination of the shuttle-based LDR components. In particular, the quadrant detector output will be used to continuously determine pointing mirror motions. Tracking of the TS is thereby maintained throughout the mission. During initial acquisition, and in the event that the TS location is lost, a search mode will automatically be initiated by the internal logic. The internal logic will also determine the range, from source/detector timing, and format the range and direction angle data for telemetry down link. Additional logic will be responsible for laser firing, photometer data recording, pointing angle, wavelength control, system check and activation, and operation control of the entire LIF system.

III. FEASIBILITY STUDY

The LIF experiment technique can be applied to the investigation of numerous species. Atomic and molecular species of interest for middle atmospheric research include O, NO, Mg, Ca, Fe (as well as their singly ionized states), in addition to O_2^+, OH, NO_2, N_2^+, Na, K, and Li. Based on criteria discussed previously for laser selection, species number density at the altitude of study, and optical properties of the target species, some of the species may be studied with existing lasers, while others require further laser development.

Na, K, and NO all appear to be excellent candidates for LIF experimentation on early tether-down TSS missions. This choice is based primarily upon both high scientific yield and the presently available laser technology required. Studies conducted at altitudes near 100 km will place the LIF photometers near the peaks of the sodium and potassium layers. Conveniently, sodium has a readily accessible resonant line at 589 nm (as does potassium at 770 nm) and is a good species for investigations of ionospheric chemistry and transport and the propagation of waves and tides. This section then, as an example of the general feasibility of LIF experimentation, addresses the feasibility of observing sodium (Na–LIF) near 100 km. The results for potassium are similar to those derived here for sodium.

There are two promising approaches to obtain the laser line at 589 nm for NA. A tunable dye laser may be employed such as the NASA/CNRS laser system[10] identified for the ER-2 DIAL program which already exceeds the laser energy requirements for the LIF configuration. The second approach yields 50–100 mJ at 589 nm by a two-wave mixing process in a nonlinear crystal, by combining a slightly tunable YAG laser at 1.06 μm with a YAG laser at 1.32 μm. The desired wavelength is obtained within only a 0.01 to 0.02-Å linewidth.[11]

In order to assess the feasibility of the Na–LIF experiment, the signal-to-background ratio must be considered. For this calculation, the laser is assumed to have a characteristic energy of 50 mJ/pulse, pulse duration of 10 ns, beam divergence angle of 0.1 mrad, and is directed down to ~100 m from the TS. The TS-mounted photometer has an aperture of 10 cm^2 and a field of view of 45° vertical × 5° horizontal.

The laser pulse is resonantly scattered by sodium atoms present in successive volumes along a conical column, and some of this scattered light enters the field of view of the photometer. The LIDAR equation can be used to calculate such fluxes F and gives $F \simeq (Ln\sigma\Delta l)\omega/4\pi$, where L is the laser energy (J) per duration of the fluorescent signal observed by the photometer, n is the concentration of Na (cm^{-3}), σ is the effective scattering cross section per particle (cm^2), Δl is the vertical length of the field of view, and ω is the solid angle of the photometer aperture as seen from the emitting volume. Using values of $n = 2\times10^3\ \mathrm{cm}^{-3}$ and $\sigma = 6\times10^{-12}\ \mathrm{cm}^2$ yields a flux of $\sim 0.2\ \mu\mathrm{W}$.

A background in the sun-lit hemisphere exists due to the resonant scattering of the solar Na-Fraunhofer light by the Na layer. The breadth at the bottom of this Fraunhofer line is large (0.1 Å) compared to the Doppler width (0.016 Å) of ionospheric Na. The residual solar flux at the bottom of the line is ~5% that of the solar continuum just outside the line.[12] An estimate of the flux of sunlight resonantly scattered into the field of view can be obtained from single-scattering theory. A value of ~0.8 nW is obtained yielding a very favorable signal-to-background ratio of ~250 per shot. This ratio dramatically increases in the nighttime hemisphere where the scattered solar background constitutes no problem.

A similar signal-to-background calculation is made for the LDR subsystem. For the described system with laser energy of 2 mJ/pulse, pulse duration of 10 ns, and a beam divergence of 1 mrad; a corner-cube reflector with a 5.08-cm diameter; and a photometer with aperture area (A) of 100 cm^2 and field of view of 3 mrad, the return signal may be calculated. For a shuttle-TS separation of 100 km the laser flux intercepted by the reflector is $\sim 5.2\times10^7$ mJ. This flux is returned, at the shuttle, in a diffraction pattern produced by the corner-cube reflector. The half-divergence angle of the pattern is 0.02 mrad and the pattern diameter at the receiver is therefore ~4.2 m. The detector area intercepts 3.8×10^{-10} mJ or 2.0×10^6 photons during a single 10-ns pulse.

For a photometer looking down at the solar illuminated Earth, the background flux is given by the expression $F^* = A\Omega I^*\Delta\lambda$, where Ω is the photometer field of view, I^* is the radiance of the Earth, and $\Delta\lambda$ the filter bandwidth. I^* is calculated using Lambert's law of reflection $I^* = aH\cos\theta/\pi$, where a is the albedo of the reflecting surface, H is the solar irradiance incident on the top of the atmosphere, and θ is the zenith angle of the sun at the reflecting area. Taking the solar irradiance on the atmosphere to be $6.5\times10^{-3}\ \mathrm{mW/cm^2\,Å}$ and using a 10-Å pass band filter and an albedo of unity, a maximum background flux of ~800 photons is obtained in 10 ns. The resultant worst case signal-to-background ratio is ~2500 demonstrating that the LDR subsystem is quite feasible.

IV. DISCUSSION

The LIF technique can provide a new method for ionospheric invertigtion, based on previously unattainable high resolution global density mappings. The flexibility of this technique to determine profiles of many trace species throughout the middle atmosphere makes this an attractive improvement over the present techniques available for probing this region. With higher-precision data gathered on a synoptic scale, an improved understanding of many ionospheric phenomena will be possible.

With this technique, several avenues of investigation are envisioned. An immediate result of LIF observations are global quasi-three-dimensional density distributions of various ionospheric species. These data are gathered over long length scales in relatively short time scales, thus facilitating the study of winds, tides, and atmospheric gravity waves. Fine structure and temporal and spatial variability of these data can yield information on diffusion, electromagnetic fields, and turbulence. Finally, the ability to probe day–night transitions and orbit relative to chemical releases will reveal basic chemical rate processes involving ionization, dissociation, and recombination.

ACKNOWLEDGMENTS

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[1] A. Gibson and M. Sanford, Nature 230, 509 (1971).

[2] G. Megie, F. Bos, J. Blamont, and M. Chanin, Planet. Space. Sci. 26, 27 (1978).

[3] J. Rowlett, C. Gardner, E. Richter, and C. Sechrist, Geophys. Rev. Lett. 5, 683 (1978).

[4] A. Segal, D. Voelz, C. Gardner, and C. Sechrist, Conference Digest, Twelfth International LASER-RADAR Conference, Aix-en-Provence, France, 1984.

[5] Atmospheric LIDAR Working Group, NASA Report No. SP-433, National Technical Information Service, Springfield, VA, 1979.

[6] NASA A.O. No. OSSA-1-84, 15 April 1984.

[7] D. McComas and H. Spence, Institute of Geophysics and Planetary Physics Report No. 2548, University of California at Los Angeles, Los Angeles, CA, 15 April 1984.

[8] D. Cobb, G. Siscoe, M. Buchwald, M. L. Chanin, P. Col[illegible] Gardner, H. Horak, R. Karl, Jr., D. McComas, A. Rosenberg, H. [illegible] T. Wilkerson, and J. Zinn, *Proposal to the National Aeronautics and Space Administration for a Bistatic LIDAR for Ionospheric Species Mapping and for a Precise Locating LIDAR for the Tethered Satellite System*, 17 July 1984(Los Alamos National Laboratory, Los Alamos, NM, 1984).

[9] R. A. Keller, R. Engleman, and E. F. Zalewski, J. Opt. Soc. 69, 738 (1979).

[10] E. Browell, G. Megie, P. Flamont, W. Hall, M. Bourdet, and J. Talbot, *Twelfth International Laser–Radar Conference*, edited G. Megie (Service d'Aeronomie du CNRS, Verriers-le-Buisson, France, 1984), abstracts.

[11] J. Bufton, C. Gardner, and C. Philbrick, Proceedings of Optical Society, Conference on Optical Remote Sensing of the Atmosphere, 15–18 January 1985, Incline Village, NV, pp. WC29-1, WC29-5, 1985.

[12] C. Allen, in *Astrophysical Quantities* (University of London, London 1963).

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SATP PROJECT

INQUIRY ON USERS REQUIREMENTS

PANEL PRESENTATION

"2ND APPLICATIONS OF TETHERS IN SPACE WORKSHOP"
VENICE, ITALY, OCTOBER 15-17,1985

N86-28423

SCIENCE AND APPLICATIONS TETHERED PLATFORM (SATP) PROJECT

- SATP IS THE SUBJECT OF A DEFINITION STUDY BY AERITALIA UNDER A CONTRACT FROM ITALY'S NATIONAL SPACE PLAN.
- SATP IS A PLATFORM, TETHERED TO THE SPACE STATION, DEVOTED TO EXPERIMENTATION IN SCIENCE AND TECHNOLOGY.
- SATP MIGHT BE A FEATURE OF THE GROWTH VERSION OF THE SPACE STATION, IN USE BY THE MID-NINETIES.
- DEMONSTRATION MISSIONS, EMBODYING THE WORKING PRINCIPLES OF SATP, MAY BE FLOWN FROM THE SHUTTLE BY THE END OF THIS DECADE.

SURVEY OF USERS REQUIREMENTS

A "CALL FOR IDEAS" QUESTIONNAIRE WAS SENT TO SOME 200 PERSPECTIVE USERS IN THE USA AND EUROPE.

THE AIM OF THE CALL FOR IDEAS WAS TWOFOLD:
- IDENTIFICATION OF SCIENTIFIC FIELDS INTERESTED IN SATP
- IDENTIFICATION OF REQUIREMENTS ARISING FROM TYPICAL EXPERIMENTS IN EACH UTILIZATION FIELD

THE QUESTIONNAIRE WAS SENT OUT BETWEEN MARCH AND APRIL 1985. ANSWERS WERE RECEIVED STARTING MAY 1985. WE EXPECT TO CONTINUE RECEIVING THEM UP TO THE END OF THE YEAR. SOME PERHAPS AS A RESULT OF THIS WORKSHOP.

CHOICE OF ADDRESSEES OF "CALL FOR IDEAS"

THE SAMPLE OF ADDRESSEES WAS LIMITED FOR REASONS OF TIME AND BUDGET.

IN ORDER TO BE ABLE TO MAKE AN EARLY SELECTION OF APPLICATIONS FOR THE DEMONSTRATION MISSIONS, SCIENTISTS WERE SELECTED THAT WERE EXPECTED TO REACT MOST QUICKLY. THAT MEANT:

- ALL CONTRIBUTORS OF PROPOSALS FOR TSS
- PARTIES IN EUROPE KNOWN BY AERITALIA TO BE INTERESTED IN THE UTILIZATION OF THE SPACE STATION, BUT POSSIBLY NOT AWARE OF THE POTENTIAL BENEFITS OF TETHERS FOR THEIR DISCIPLINES (E.G. THE MICROGRAVITY COMMUNITY).

EXPERTS OF TETHER DYNAMICS WERE ALSO INCLUDED AS THEY COULD PROVIDE USEFUL SUGGESTIONS (AND WORDS OF CAUTION).

FEATURES OF THE PLATFORM

THE FOLLOWING FEATURES OF THE PLATFORM WERE HIGHLIGHTED IN THE DOCUMENTATION ACCOMPANYING THE QUESTIONNAIRE:

o A TETHERED PLATFORM IS THE ONLY TRULY CO-ORBITING PLATFORM THE SPACE STATION MAY GET

o IT IS IN PRINCIPLE EASILY ACCESSIBLE

o THE TETHER MAY ISOLATE THE PLATFORM BOTH FROM CONTAMINATION AND FROM DYNAMICAL DISTURBANCES ORIGINATING IN THE SPACE STATION

o THE TETHER PROVIDES AN ADJUSTABLE LOW-G ENVIRONMENT

o POWER/THRUST GENERATION BY TETHER MAY PROVIDE AN ADVANTAGEOUS ALTERNATIVE TO CONVENTIONAL SOLUTIONS

THE POSSIBILITY OF TEST MISSIONS IN A SHUTTLE CONTEXT WAS ALSO ADDRESSED.

SUMMARY OF RESULTS

ABOUT 20 PERCENT ANSWERS HAVE BEEN RECEIVED TO DATE

THE FOLLOWING DISCIPLINES ARE REPRESENTED (IN ORDER OF RELATIVE FREQUENCY):

- MICROGRAVITY APPLICATIONS
- PLASMA PHYSICS
- EARTH AND PLANETARY SCIENCE
- ASTRONOMY
- TETHER DYNAMICS

IDEAS RANGE FROM:

- BIOTECHNOLOGY, MATERIALS PRODUCTION, PHARMACEUTICAL PRODUCTION, PHYSICAL CHEMISTRY, TO
- MAPPING OF PLASMA MOTION, PLASMA WAVE PROPAGATION, BEAM PLASMA INTERACTIONS, TO
- GEOMAGNETIC FIELD MAPPING, COSMIC DUST COLLECTION, SIMULATION OF PLANETARY ENVIRONMENTS, REMOTE SENSING.

SUMMARY OF RESULTS (CONT'D)

ASTRONOMICAL POINTING APPLICATIONS HAVE NOT RAISED GREAT INTEREST SO FAR, MAINLY BECAUSE:

- o PRESENT AND PLANNED FREE-FLYING OBSERVATORIES SATISFY SCIENTIFIC NEEDS BETTER THAN SPACE STATION RELATED ONES
- o STABILITY PROPERTIES OF A TETHERED PLATFORM HAVE STILL TO BE PROVEN

INVESTIGATION OF STABILITY AND POINTING FEATURES IS NEVERTHELESS CONTINUING. ONCE FEASIBILITY IS PROVEN, SCIENTISTS MAY RECONSIDER SATP VALUE.

MICROGRAVITY APPLICATIONS

THE MICROGRAVITY SCIENCE COMMUNITY'S REACTION TO SATP WAS MOST ENCOURAGING.

IDEAS ADVANCED INCLUDE:

- o BIOTECHNOLOGY
- o CRYSTAL GROWTH
- o RADIOBIOLOGY
- o PHARMACEUTICAL PRODUCTION
- o ENVIRONMENTAL EFFECTS ON CHEMICAL REACTIONS
- o DIFFUSION AND CONVECTION PHENOMENA

MICROGRAVITY APPLICATIONS (CONT'D)

STATED REASONS FOR SUCH INTEREST ARE:

- o LARGE NUMBER OF OPPORTUNITIES OFFERED BY A PERMANENT FACILITY
- o AVAILABILITY OF HIGH POWER
- o GOOD PROJECTED ENVIRONMENT (LOW, STABLE RESIDUAL ACCELERATION FIELD, NO CONTAMINATION FROM SPACE STATION)
- o CAPABILITY OF TETHER SYSTEM OF PROVIDING A MICRO-G FIELD VARIABLE IN BOTH MAGNITUDE AND DIRECTION

FOR THE PRACTICAL IMPLEMENTATION OF SUCH GOALS, A MICRO-G LAB MOBILE ALONG THE TETHER (SPACE ELEVATOR) IS UNDER STUDY AT AERITALIA.

EARTH AND PLANETARY PHYSICS APPLICATIONS

A LARGE NUMBER OF PROPOSALS CONCERNS APPLICATIONS OF THE ELECTRODYNAMIC TETHER. THESE ARE ACTIVE EXPERIMENTS, I.E. PERTURBATIONS ARE INDUCED IN THE MEDIUM SURROUNDING THE TETHER SYSTEM AND THE RESULTING PHENOMENA ARE RECORDED.

SOME EXAMPLES:

o PLASMA WAVE PROPAGATION
o BEAM - PLASMA INTERACTIONS
o MAPPING OF THERMAL PLASMA MOTION

EARTH AND PLANETARY PHYSICS APPLICATIONS (CONT'D)

ANOTHER GROUP OF IDEAS CONCERNS PASSIVE, SURVEY-TYPE APPLICATIONS:

- o GEOMAGNETIC FIELD AND FIELD ANOMALY MAPPING
- o MEASUREMENT OF ELECTRIC FIELDS IN THE ATMOSPHERE
- o EARTH OBSERVATION BY HIGH RESOLUTION SOLID STATE SENSORS
- o STEREOSCOPIC PHOTOGRAPHY

MOST SUCH IDEAS ARE DEVELOPMENTS OF PROPOSALS ALREADY SUBMITTED FOR TSS.

ORIGINAL IDEAS INCLUDED:

- o SIMULATION OF PLANETARY ENVIRONMENTS
- o COSMIC DUST COLLECTION

SUMMARY OF REQUIREMENTS

APPLICATION TYPE	TETHER	G-LEVEL	SATP ATTITUDE CONTROL/MEAS.	DYNAMIC ENV. CONTROL	MISSION DURATION	CLEANLINESS	AUTOMATED/ CREW CONTROL	DATA STORAGE	POWER
MICRO-G	NON CONDUCT.	10^{-5}g	/	ESSENTIAL	180 ^{d}	HIGH ALL CONTAM.		Mbits	20-50 KW
ELECTRODYN.	COND.	/	10^{-1}deg	/	15^{d}	ESSENTIAL EMC	INTERACTIVE CREW CONTROL	Mbits	0.5 KW
SURVEY/MAPPING	NON. CONDUCT.	/	10^{-1} 10^{-3}	/	45- 90^{d}	DC-FIELDS RELEVANT	AUTOM	Kbits	0.1 KW
ASTRONOMY	NON CONDUCT.	/	10^{-4} 10^{-5}	ESSENTIAL	$90\text{-}360^{d}$	IMPORTANT	AUTOM.	Kbits	0.5 KW

CONCLUSIONS: PRESENT STATUS OF WORK

WITHIN THE END OF THE YEAR RECOMMENDATIONS WILL BE SUBMITTED FOR THE DEMONSTRATION MISSIONS. THE MOBILE MICROGRAVITY LAB (SPACE ELEVATOR) WILL RECEIVE THE HIGHEST PRIORITY, GIVEN THE INTEREST RAISED AND THE PROMISE OF TECHNICAL FEASIBILITY.

AS FOR SPACE-STATION SATP, CONCEPTUAL DESIGNS WILL BE DEVELOPED FOR APPLICATIONS IN MICROGRAVITY, ELECTRODYNAMICS, SURVEYS AND ASTRONOMY.

ADDITIONAL IDEAS AND SUGGESTIONS ARE WELCOME.

HIGH RESOLUTION REMOTE SENSING MISSIONS
OF A TETHERED SATELLITE

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Abstract

This paper deals with the application of the Tethered Satellite (TS) as an operational remote sensing platform. It represents a new platform capable of covering the altitudes between airplanes and free flying satellites, offering an adequate lifetime, high geometric and radiometric resolution and improved cartographic accuracy.

Two operational remote sensing missions are proposed: one using two linear array systems for along-track stereoscopic observation and one using a synthetic aperture radar combined with an interferometric technique. These missions are able to improve significantly the accuracy of future real time cartographic systems from space, also allowing, in the case of active microwave systems, the Earth's observation both in adverse weather and at any time, day or night.

Furthermore a simulation program is described in which, in order to examine carefully the potentiality of the TS as a new remote sensing platform, the orbital and attitude dynamics description of the TSS is integrated with the sensor viewing geometry, the Earth's ellipsoid, the atmospheric effects, the sun illumination and the digital elevation model.

In order to test and check this model and to focus the attention of remote sensing users and researchers, a preliminary experiment has been proposed which consists of a metric camera to be deployed downwards during the second Shuttle demonstration flight.

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Introduction

In the last few years several experiments of remote sensing have been conducted using free flying satellites at different altitudes. The results have shown the need for an increasing performance of future advanced multispectral imaging systems.

First, it is likely that significant improvement in sensor resolution will be required. Secondly, it may be desiderable to use significantly narrower spectral bandwidths. In addition, many remote sensing disciplines have stated a need for high sensitivities capable of detecting a few tenths of a percent change in reflectivity for background reflectivities in the order cf 5%. Lastly, increasing resolution must be combined with stereoscopic coverage particularly for completion and revision of world's cartography.

Based on these considerations, new sensor technologies have been developed and new space missions have been approved such as the French SPOT satellite, the U.S. LANDSAT D and Large Format Camera and the German MOMS and RMK etc. The Space Shuttle now gives the unique capability of a low orbit in which different remote sensing systems can be tested, before their operational life.

In spite of these actual and future improvements, there are practical limitations in the achievable geometric and radiometric resolutions and in the height measurement accuracy from space.

The unique capability of the Tethered Satellite System (TSS) to deliver payloads to altitudes down to 120 Km and to make relevant measurements on a global scale allows the observation of the Earth and the atmosphere with sensors of simplified design and/or of better performance with respect to those of platforms at higher altitudes. This is particularly true when high geometric resolution and S/N ratio are required using different narrow spectral bands. The Tethered Satellite (TS) deployed by the Shuttle or by a future space station is candidate as an operational platform capable of covering the altitudes between airplanes and free flying satellites. Furthermore it offers unique advantages in improving the results obtainable by push-brooms and passive and active microwave sensors.

The first part of this paper deals with a preliminary analysis of the different advantages and problems of two potential remote sensing missions, which allow the stereoscopic observation of the Earth by using two solid state sensors or a Synthetic Aperture Radar (SAR), onboard the TS.

The second part gives a synthetic description of the computer simulation program developed by the authors (in which the TS orbital and attitude dynamics is integrated with the sensor observation) and of the experiment proposed for the second Shuttle demonstration mission.

Remote sensing missions of a multipurpose TS deployed by a Space Station

Most applications of a remote sensing require a repetitive coverage of large areas of the Earth and, consequently, need an adequate satellite lifetime. Therefore, even though the TS deployed by the Space Shuttle is a platform particularly suited for testing new sensors and for carrying out scientific experiments, its operational use as a high resolution remote sensing platform is strictly connected to the development of space stations. The flexibility offered by a recoverable multipurpose tethered platform, deployable at different altitudes and able to exploit all the advantages of being connected to the space station (power, data handling, human intervention, etc.) will permit several remote sensing experiments to be conducted such as:

- development of a modular multi-altitude sensor;
- integration of data at different resolution from different platforms;
- high geometric and radiometric resolution in the visible and infrared;
- development of active and passive microwave systems using tethered antennas;
- analysis of the bidirectional reflectance coefficient using a multiangle approach.

Taking into account the inadequacy of current topographic map coverage to meet worldwide needs for economic planning and development, the TS offers in particular new possibilities for creation and maintenance of cartographic information. Therefore, in the following, special emphasis is devoted to the operational application of the TS to topographic and thematic mapping, by giving two examples of stereoscopic observation using a linear array and a SAR interferometer system.

Photogrammetric cameras and frame sensors will not be considered due to the fact that their application and improved performance at lower altitudes are well known.

The along-track stereoscopic coverage using two linear arrays (fig. 1) requires particular constraints on the satellite position and attitude dynamics, which are analyzed in the following, in order to identify the achievable scale improvement using the TSS, under the assumption of a circular orbit and the same EIFOV, with respect to the deployer (DP) or a free flying (FF) satellite. The TS gives a small improvement of the integration time (T) and a small increase of the time interval between the fore and aft camera observations in comparison with a free-flying satellite at the same altitude (fig. 2). The dashed lines show the ratio of the integration time between the TS and the deployer. The sensor simplified design is mainly due to the reduced optics aperture and focal length (fig. 3).

The basic "heighting" equation for convergent linear array image stereopairs (fig. 1) is (ref. 1):

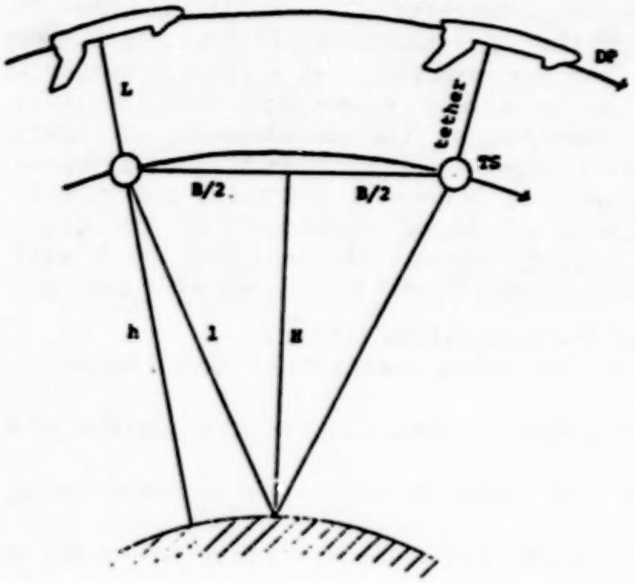

Fig. 1 Fore and aft camera stereoscopic viewing geometry from the tethered satellite.

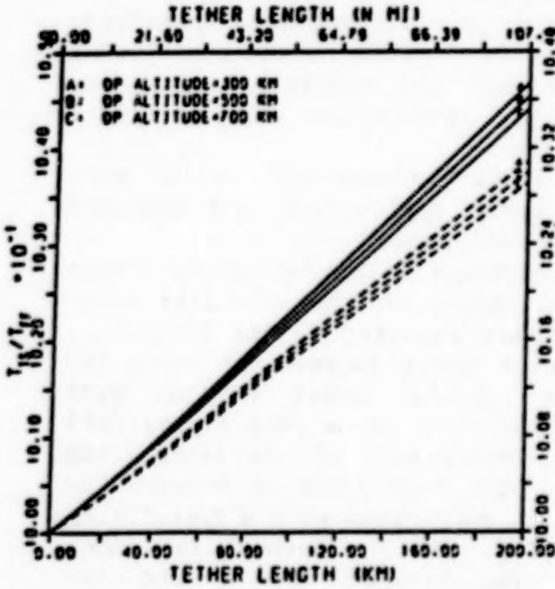

Fig. 2 Ratio between the integration times of the TS and of the FF satellite and of the DP (dashed lines) as function of tether length.

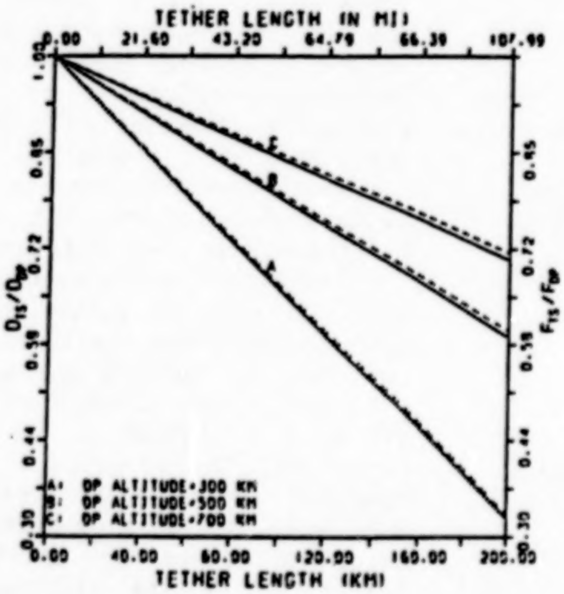

Fig. 3 Ratio between the optics aperture diameters and the focal lengths (dashed lines) of the TS and of the DP, as a function of tether length.

$$\Delta h = \frac{\Delta p}{(B/H)} SF$$

where Δh is the height difference, Δp is the difference in x-parallax, SF is the image scale factor, B/H is the base to height ratio.

The ratio between the spot height error (Z-error, ZE) of the TS and DP is shown in fig. 4, using two different values of the ratio $(B/H)_{DP}/(B/H)_{TS}$. This figure points out that the increased tether length, which reduces the sensor EIFOV and swath width, decreases the TS Z-error, under the same B/H ratio of the deployer or allows reduction of the TS B/H ratio under the same Z-error. The advantages of using the TS with respect to the deployer are made more evident by decreasing the DP altitude.

Under the same B/H ratio, the TS needs a time interval between the fore and aft cameras shorter than the interval of the deployer. This is important from the geometrical point of view, since any perturbation in the satellite attitude, altitude or velocity will be translated into geometric distortions in the imagery, giving rise to loss of planimetric and vertical cartographic accuracy (fig. 5). Under the same along-track angular error, at lower altitudes, it is possible to achieve a better Z-error (fig. 6).

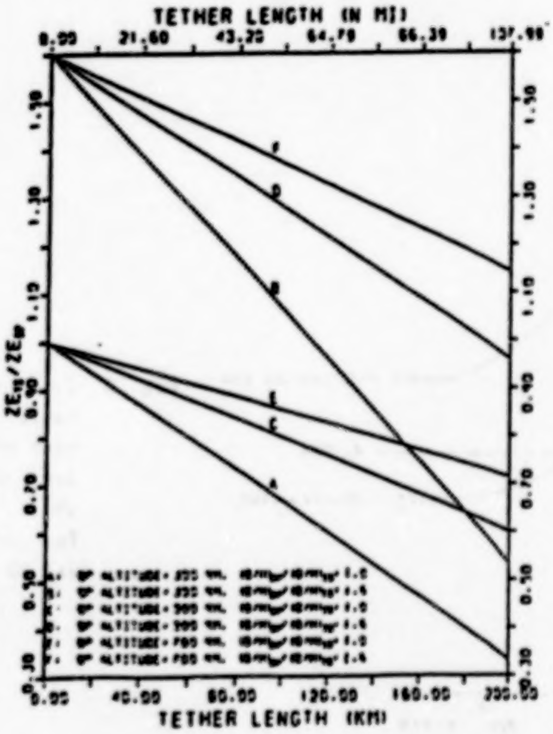

Fig. 4 Ratio between the spot height error of the TS and the DP as a function of tether length.

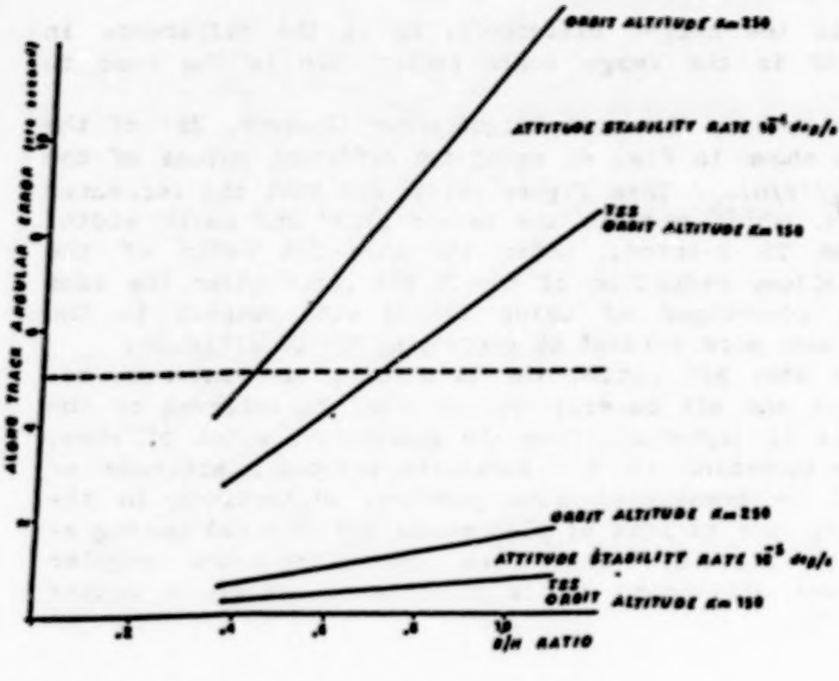

Fig. 5 Along-track angular error vs. B/H ratio for different attitude stability rates and orbit altitudes.

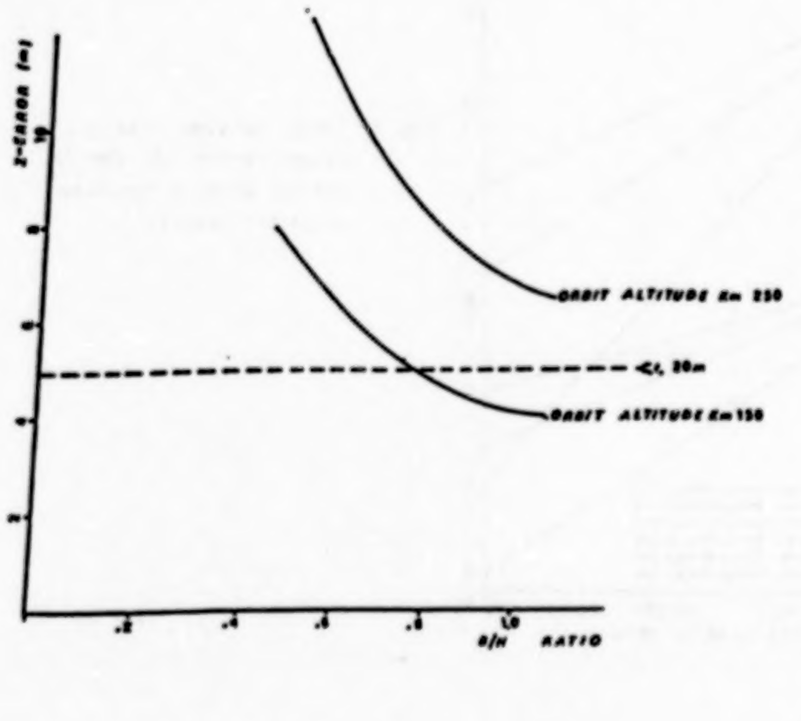

Fig. 6 Z-error vs. B/H ratio for different orbit altitudes. Dashed line shows the value for contour interval 20 m.

The along-track stereoscopic coverage involves the reduction of the swath width, due to the Earth's rotation between the fore and aft camera observations. A yaw motion has been proposed (ref. 2) to reduce the lack of coverage.

In the case of the TS, the decrease of Δt between two successive observations of the same point is partly balanced by the swath width reduction. This effect, at the ascending node, is shown by the following equations, in which the chord is assumed equal to the arc (fig. 1), K represents the ratio between the Earth's displacement and the swath width (W), during the fore and aft camera observations, $R_{\oplus}$ is the Earth's radius, μ is the Earth's gravitational constant, and $\omega_{\oplus}$ is the Earth's rotational rate:

$$K = \frac{\omega_{\oplus} R_{\oplus} \left(\frac{B}{H}\right) (H + L)}{W_{DP} \left(\frac{R_{\oplus} + H}{R_{\oplus} + H + L}\right) \sqrt{\frac{\mu}{R_{\oplus} + H + L}}}$$

$$\frac{K_{TS}}{K_{DP}} \doteq \frac{\left(\frac{B}{H}\right)_{TS}}{\left(\frac{B}{H}\right)_{DP}} \left(\frac{R_{\oplus} + H + L}{R_{\oplus} + H}\right)$$

In this case a substantial gain in the effective stereoscopic coverage can be obtained using the possibility of reducing the B/H ratio as a function of the tether length.

As previously shown a decrease of the B/H ratio improves the attitude stability Z-error and worsens the measurement Z-error.

The swath width is connected to the EIFOV and data rate as shown in figs. 7-8. The TS offers the possibility of decreasing the data rate (for a constant ratio Earth's displacement/swath width) and this effect is increased by decreasing the EIFOV.

A representative example is given by a space station orbiting at an altitude of 500 Km, having, as an operational module, a TS that can be deployed to 200 Km. The following root mean square Z-errors must be taken into account to get an estimate of the final scale:

- measurement error (fig. 4), assumed equal to 1/2 pixel;
- error due to the attitude stability rate (10^{-5} °/s);
- miscellaneous errors, assumed less than 1 pixel.

Table 1 illustrates also the scales that can be reached at different altitudes.

Another method that can be proposed for high resolution observation with contemporaneous terrain height measurement is the interferometric technique which consists of two antennas one above the other.

If two vertically spaced physical antennas are carried along parallel paths by the deployer and the TS, the outputs of the two synthetic antenna systems can be combined to form a synthe-

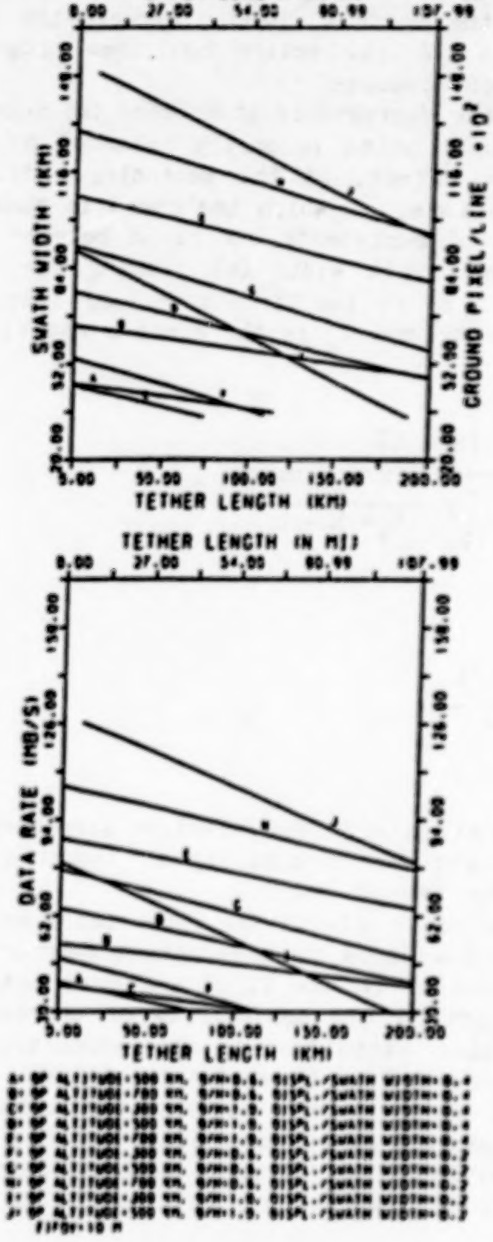

Fig. 7 Swath width and data rate as a function of tether length for different deployer altitudes, B/H ratios, Earth's displacement/swath width ratios and EIFOV = 10 m.

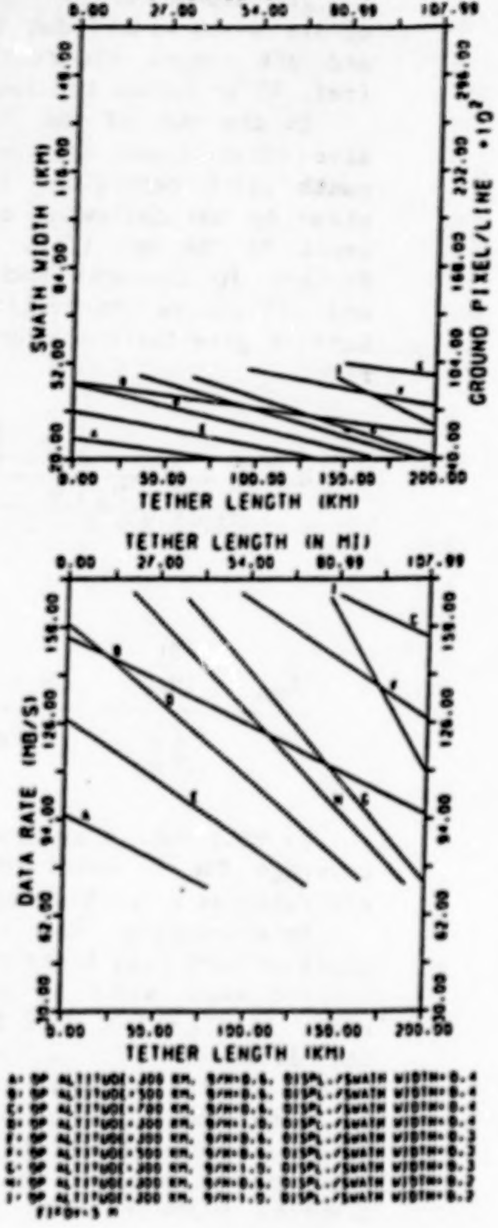

Fig. 8 Same as fig. 7 for EIFOV = 5 m.

RMAS SPOT HEIGHT SE (m)	MAP SCALE	TS ALTITUDE (Km)	EIFOV (m)	ATTITUDE STABILITY SE (m)	MEASUREMENT SE (m)	MISCELLANEOUS SE (m)	TOTAL SE (m)
±6-15	1:100,000	500	10	±7.0	±5	±8	±11.7
		400	8	±4.6	±4	±6	±8.6
±6	1:50,000	300	6	±2.6	±3	±4	±5.6

Table 1 Achievable scales of topographic maps from different altitudes (B/H = 1, attitude stability rate 10^{-5} °/s).

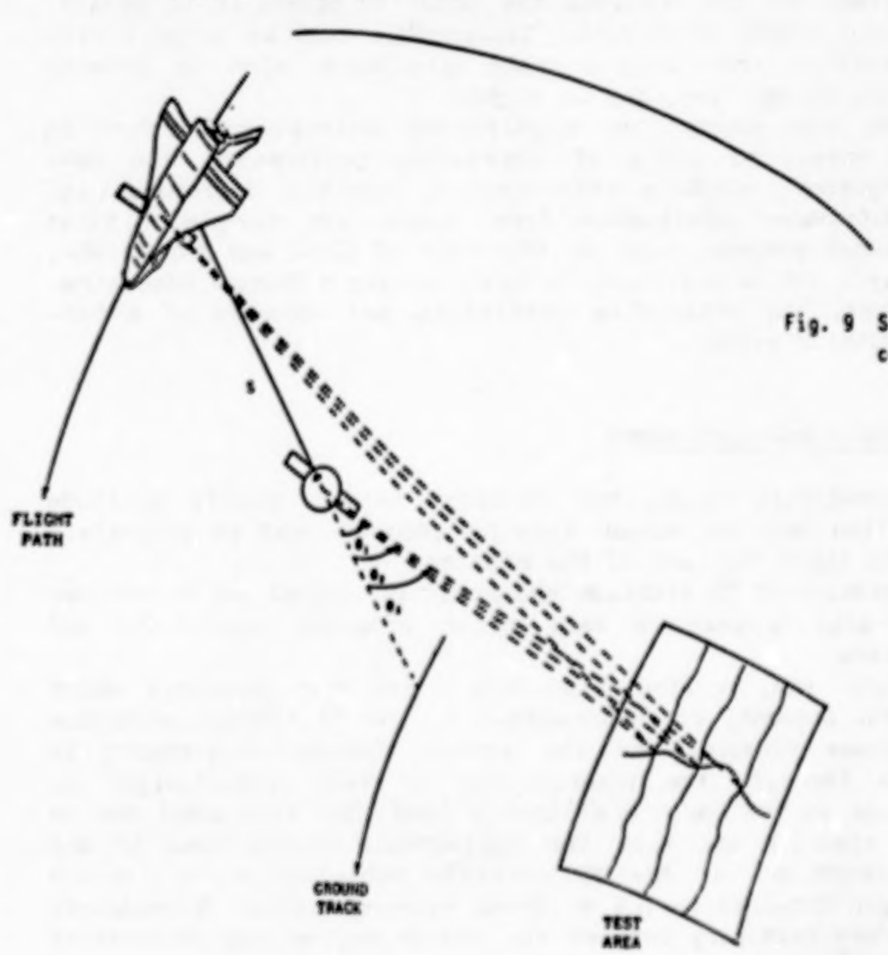
S
θ_1
θ_2
θ_3
FLIGHT PATH
GROUND TRACK
TEST AREA

Fig. 9 SAR interferometer configuration.

tic interferometer (fig. 9). The fine resolution image of the terrain is provided by synthetic aperture radar technology (ref. 3) and the height measurement is made by radar interferometry (ref. 4). Therefore two images are produced: one using the normal synthetic aperture radar image obtainable by a single physical antenna, and one using two antennas to produce the null pattern that can be superimposed on the "true image".

Nulls will appear in the final image at certain predetermined angles of incidence given by

$$\theta_n = \cos^{-1} \frac{(2n+1)\lambda}{2s}$$

where λ is the wavelength and s is the spacing between the deployer and the TS.

The range measurement allows the determination of the slant range R_n to a point on the null, and, therefore, the terrain profile can be computed for each line. The density of profiles can be increased by detecting other phases. The increasing distance between the deployer and the TS will decrease the spacing between nulls, which is directly related to profile accuracy.

Therefore the TSS provides the means to obtain or to update, by computer aided techniques, topographic maps at large scales not achievable from single space platforms, also in adverse weather and at any time, day or night.

Taking into account the significant international effort in the development of SAR's of increasing performance, the SAR-interferometer technique represents a potential improvement of active microwave application from space. For example a joint international program, such as the case of SIR-C and X-SAR (USA, FRG, Italy), can be envisaged to test, during a Shuttle demonstration flight, the achievable resolution and accuracy of a SAR-interferometer system.

A numerical simulation model

As previously shown, the relation between the TS attitude and position and the sensor viewing geometry must be accurately studied to limit the cost of the mission.

The problem of TS attitude and position control and determination is also present in many other proposed experiments and applications.

To this end, a simulation model has been developed which takes into account, contemporaneously, the TS orbital mechanics and attitude dynamics and the sensor observation geometry in order to identify the intersection of each line-of-sight or slant range on the Earth's ellipsoid (ref. 5). This model can be used to simulate and test the appropriate control laws of the tether length and of the TS attitude subsystem or to correct real images obtained during a remote sensing mission. A trade-off is therefore necessary between the design engineering constraints and the cost of a sophisticated preprocessing system.

The model developed to describe the TSS orbital dynamics is similar to the Skyhook approach (ref. 6). Moreover also the TS attitude dynamics is considered, taking into account the torques due to the tether tension and aerodynamic forces.

The sensor viewing geometry is simulated and the intersection of the line-of-sight with a digital elevation model, taking into account the atmospheric effects, is computed (ref. 7).

Different tests have been conducted to simulate the sensor observation from the TS, deployed by the Shuttle or a space station. The results have shown that, in-plane and out-of-plane oscillations do not affect significantly the geometric errors of the images taken during the short observation time interval. These oscillations and the longitudinal one can be damped by using an adequate tether control law.

As far as attitude is concerned, a deeper study is needed to identify the attitude measurement and control systems of the future multipurpose platform.

A meaningful test to check and improve the simulation model is the second demonstration mission where the TS will be deployed downwards to 100 Km.

To this end the authors have proposed using a lightweight metric camera to conduct a remote sensing experiment with the following objectives:

- to obtain high resolution stereoscopic coverage of several test sites for topographic and thematic applications;
- to integrate ground control points taken on the images with engineering and ancillary data for an improvement of the attitude and positional analysis of the TS during deployment, retrieval and station keeping;
- to focus the research community attention on the potentiality of the TS as a new remote sensing platform.

The present data rate necessarily implies the use of a film camera. This camera could provide different scales of coverage at different altitudes, depending on the required scale of the final map product. Tab. 2 shows the photographic scales obtainable during the proposed experiment with different focal lengths (F).

H Km \ F cm	10	20	30
220	2,200,000	1,100,000	733,000
190	1,900,000	950,000	633,000
160	1,600,000	800,000	533,000
130	1,300,000	650,000	433,000

Table 2 Preliminary photographic scales from the TS metric camera.

The photographic scale is also connected to the elevation and position accuracy (ref. 8).

At this stage it is possible to give only a preliminary description of the metric camera characteristics, shown in tab. 3.

f/number	4
focal length	300 mm
film format size	11.5x11.5 cm
field of view	22°
ground resolution	10 m
ground footprint	50x50 Km
weight	15 Kg
volume	10 dm^3

Table 3 Preliminary characteristics of the metric camera.

The camera will utilize film supplied in a cassette of approximatively 450 frames, with possibly a spacecraft forward motion compensation. Different time intervals between a photographic pair will be allowed, so providing various B/H ratios. An area of $3.75x10^5$ Km^2, equivalent to a strip of 7500 Km, will be covered with 35% overlap stereopairs and a B/H ratio of .25.

The metric camera accomodation in the TS is shown in fig. 10. The scientific package is allocated on the bottom, using an optical window at the end of a 18 cm diameter cylinder box, which has already been designed by Aeritalia (ref. 9). The upper part is connected to the P/L floor, equipped with special antivibration mounts.

Gaseous effluents eventually flowing near the optical window can affect the radiometric and geometric quality of the data and the external camera components through deposition and accumulation. The TSS gaseous effluents are of minor importance due to the thrusters distribution.

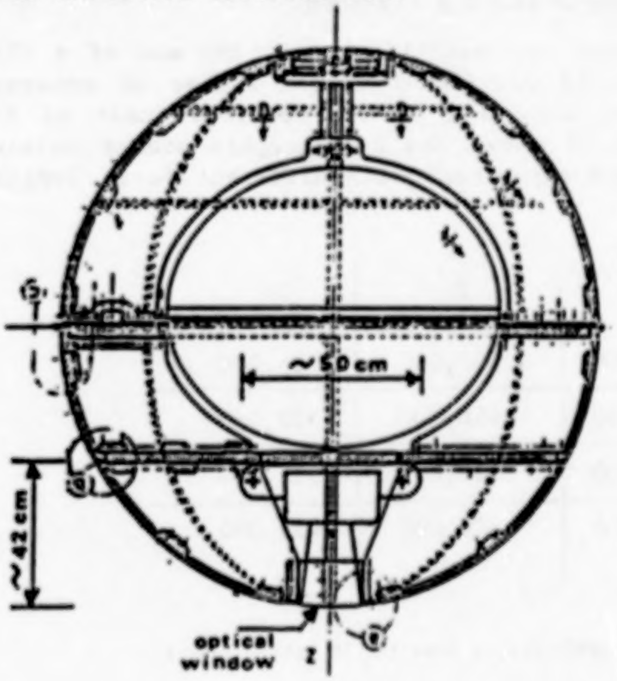

Fig. 10 The metric camera accomodation.

Determining the extent to which measurements may be degraded by spacecraft effluents and by atmosphere/satellite interactions requires a detailed study that can be integrated with other specific experiments.

By analyzing the stereoscopic photographs it will be possible to identify several Ground Control Points (GCP's), whose geographic coordinates and height are precisely known. The TS orbital and attitude simulation will be integrated with conventional photogrammetric techniques (ref. 10), and a more precise dynamics description will be carried out by using the GCP's and the satellite ancillary data.

The identification of GCP's requires, preferably, the observation of areas on which an appropriate cartography is available. Therefore the deployer orbit could be optimized by also taking into account the sun illumination condition. To this end different orbits are under study, as shown in the two examples of figs. 11-12. Both show the ground tracks relative to a TS 36 hours mission and to a solar elevation angle greater than 30°.

Conclusions

The preliminary analysis, which has been carried out to verify the potentiality of the TS as a remote sensing platform, shows different advantages and peculiarities, particularly when high resolution and stereoscopic coverage are required.

In any case it is necessary to improve significantly the TS data rate and power (even using the tether as a power and communication line), and the control subsystems of the tether length and the TS attitude.

Also the technology of future space sensors requires taking into account the potentialities and new applications offered by the TS.

This new platform must be designed as a multipurpose satellite connected to the future space stations.

The simulation model, briefly described in this paper, requires a further substantial improvement which, on one hand, must be concentrated on the control laws, the tether behavior and the fluid oscillations in the containers, and, on the other hand, must utilize ad-hoc experiments to test the different model aspects.

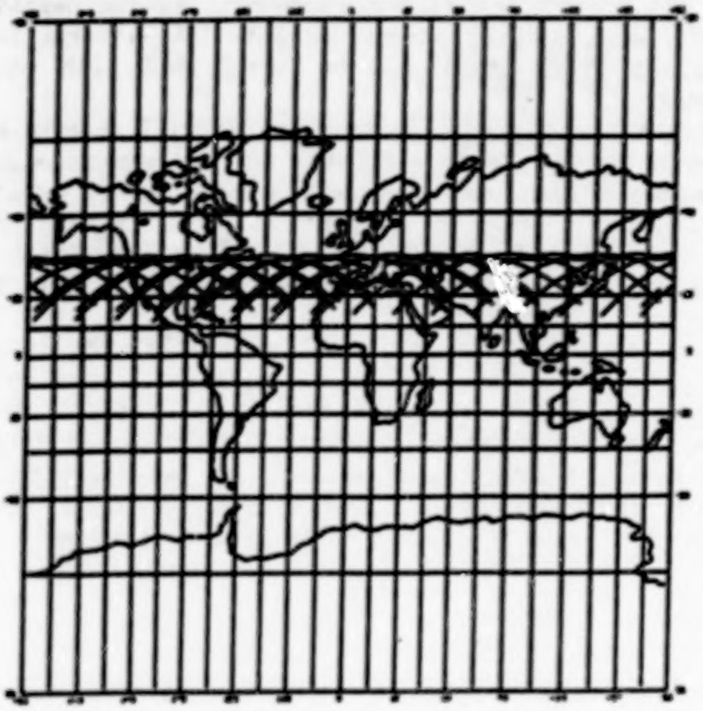

Fig. 11 Ground track of the drifting prograde orbit (deployer altitude Km 250, inclination 47°, nodal period 5363 s, repetition factor 15+4/5).

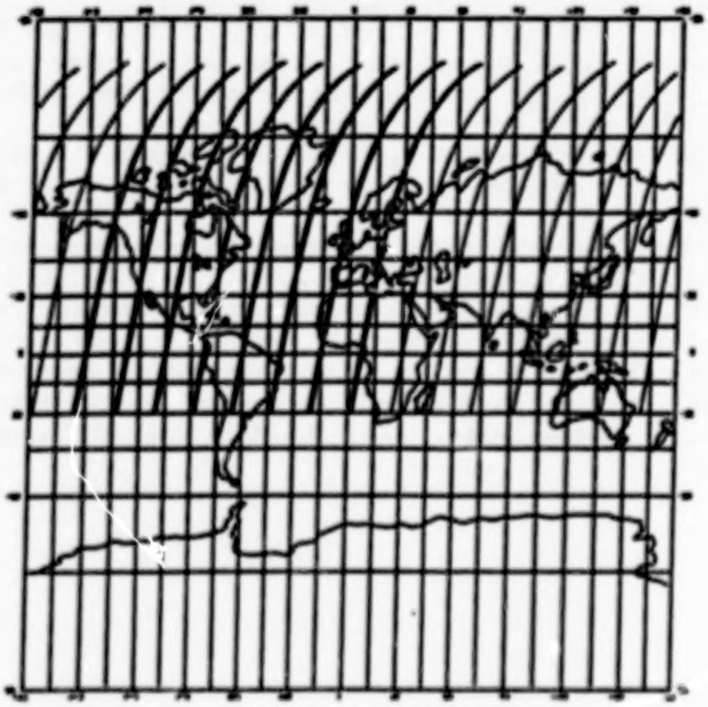

Fig. 12 Ground track of the drifting sunsynchronous orbit (deployer altitude Km 250, inclination 96.5°, nodal period 5378 s, repetition factor 16+1/15).

References

1. Welch, R., 1980. Measurement from Linear Array Camera Images, Ph. Eng. and Rem. Sens., Vol. 46, No. 3, pp. 315-318.
2. Jet Propulsion Laboratory, 1979. Preliminary Stereosat Mission Description, NASA/JPL Report 720-33, May 30.
3. Harger, R.O., 1970. Synthetic Aperture Radar Systems, Theory and Design, Academic Press.
4. Ulaby, F.T., R.K. Moore, and A.K. Fung, 1982. Microwave Remote Sensing, Active and Passive, vol. II Radar Remote Sensing, Addison-Wesley.
5. Vetrella, S., and A. Moccia, 1985. Influenza della posizione e dell'assetto del Tethered Satellite System nell'osservazione stereoscopica dallo spazio, VIII Congr. AIDAA, 052-85.
6. Kalaghan, P.M., et al. 1978. Study of the Dynamics of a Tethered Satellite System (Skyhook), Smithsonian Inst. Astroph. Obser.
7. Moccia, A., S. Vetrella. An integrated approach to geometric precision processing of spaceborne high resolution sensors, accepted Int. Journal of Remote Sensing, Taylor & Francis.
8. Doyle, F.J., 1979. A Large Format Camera for Shuttle, Ph. Eng. and Rem. Sens., Vol. 45, No. 1, pp. 73-78.
9. Aeritalia, 1983. TSS, Satellite Module Baseline Design Review Presentation, Turin.
10. Ghosh, S.K., 1979. Analytical Photogrammetry, Pergamon Press.

Future Applications of Tethers for Basic Scientific Research

Harris Mayer

Application	Orbit	Attached Mass, M(kg)	Tether Type and Length from Center Mass L,(km)	Ideal Tether Mass Ratio	Era	Technological Risk For That Era
1. Fundamental Physical Laws						
1.1 Magnetic monopole detection by induced current in superconducting loops of space web	LEO sun-synchronous: 500 km circular polar 97.6° inclination	10^4	0.5 centrifugal web circumferential and radial members $W = 10^{-2} sec^{-1}$	2.5×10^{-5}	Mid-term	High
1.2 High accuracy measurement of gravitational red shift of Mossbauer x-rays, visible laser, H maser radiation over tethered 100 km vertical path	LEO Ex: 500 km circular 28°	10^3	100 Gravity gradient 0.1 stabilized dual path (vacuum and glass fiber)	0.1	Near term	Medium
1.3 Michelson-Morley experiment with laser light in centrifugally stabilized tether geometry to measure constancy of velocity of light	LEO Ex: 500 km circular 28°	10^3	5 crossed tethers centrifugally stabilized $W = 10^{-2} sec^{-1}$	2.5×10^{-3}	Near term	High
1.4 Accurate measurement of gravitational constant G by torsion balance at a low "g" position on a tether. Desired accuracy 1 in 10^6	LEO Ex: 500 km circular 28°	10^3	1 Gravity gradient	0.6×10^{-4}	Near term	Medium - needs uniform test masses.

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Future Applications of Tethers for Basic Scientific Research (Cont.)

Harris Mayer

	Application	Orbit	Attached Mass, M(kg)	Tether Type and Length from Center Mass L,(km)	Ideal Tether Mass Ratio	Era	Technological Risk For That Era
2	Fundamental Structure of the Universe						
2.1	Detection of gravitational waves from super nova collapse, galactic blackholes, by induced tether stretching vibrations in centrifugally stabilized tether at a Lagrange point. Fundamental frequency tuned by tether strain	Stable at Lagrangian point	10^3	10^3 centrifugally stabilized $W = 10^{-4}$ sec^{-1}	10^{-2}	Mid-term	Medium
2.2	Anisotropy of 2.7 K remnant microwave radiation from big bang genesis by 100 m "end fired" crossed long linear array microwave antennas, spin stabilized. Detect $_2 = 1$ cm and $= 0.5$ cm $= (\ /L)^2 = 10^{-8}$	LEO Ex: 500 km circular 63° Spin axis precesses	10^3	0.1 centrifugally stabilized $W = 0.1$sec^{-1}	10^{-4}	Mid-term	Medium
2.3	Soft x-ray imaging telescope using 100 m egg crate reflection optics to detect noisy galaxies, possibly with active black hole centers.	LEO Ex: 500 km circular 28°	10^4	0.1 – Egg crate electrodynamically stabilized. Local surface gravity gradient stabilized	10^{-7}	Mid-term	High

Application	Orbit	Attached Mass M, kg	Tether Length and Type L, km	Ideal Tether Mass Ratio m/M	Ideal Tether Mass m, kg
3. Large Experimental Facilities					
3.1 Large diameter synthetic array radio telescope	HEO, ecliptic 3.6×10^4 km circular	5000	10 variable centrifugal	0.01	50
3.2 Ring aperture radio telescope (10 km diam)	LEO, ecliptic 500 km, circular	1000	10 centrifugal	0.03	30
3.3 Line array, end fired, microwave antenna	LEO, any 500 km, circular	1000	100 Gravity Gradient	0.1	10
3.4 Electrodynamic Tether as a magnetic field mapper	Any	Intrinsic tether mass	1000 conducting	-	100
3.5 Synthetic aperture visible light telescope (two 2m mirrors at end of rotating 2 km tether). Resolve extra solar planets from primary at 40 light yr.	LEO, any 500 km, circular	500	1 Centrifugal	3×10^{-4}	.15

4. Equipment for Solar System and Planetary Science

4.1 Spacecraft with rotating centrifugally stabilized tether legs as planetoid Daddy Long Legs stalker.

1. Measure radioactivity	4. Surface sample retriever
2. Implant detectors	5. Explore 4 surface by pulling on tether legs which hold onto surface
3. Seismic thumper	

4.2 Retrograde 10 km tethers for lengthened observation of planetoids at 1 km/sec flyby velocity.

4.3 Plowing tether tips to measure surface properties of planetoids at 1 km/sec flyby velocity. Useful to change direction of flyby.

4.4 Deploy and retrieve balloons at high altitudes in planetary atmosphere from orbiting spacecraft with retrograde rotating tethers. Useful on Mars? and major Jovian and Saturnian satellites with atmospheres.

4.5 Precision centrifugally stabilized tether in very low orbit suspended from mother craft in moderately low orbit around major satellite or minor planet. Perturbations in motion are related to gravitic anomalies. Vibration rotation perturbations observed from mother ship.

4.6 Drag tethers for high altitude atmospheric vs gravitic effects. Dragged from orbiting planetary exlorer.

5. A Major Mission

Transfer a 10^6 ton asteroid from main belt to LEO using H bomb explosions for propulsion. Separate asteroid into 2 parts with electrodynamic tether $L = 45$ km between them to generate power for industrial use - refining asteroidal material. Reboost as necessary with H bomb propulsion. Net effect is to use H bomb energy, stored in orbital energy, for industrial purposes.

ELECTRODYNAMICS PANEL

ELECTRODYNAMICS PANEL SUMMARY REPORT

I. INTRODUCTION

The Electrodynamic Interactions working panel met for two full day sessions on Wednesday and Thursday, 16 and 17 October 1985. The activities for the two days were broken down in the following manner:

WEDNESDAY, 16 OCT 1985: Participants with prepared materials made presentations to the working panel. There were seven individuals with eight presentations covering power and thrust generation applications, laboratory and space experiments and demonstrations, and antenna applications. At the close of day, the panel drew up a list of issues to be considered further in the Thursday session. The issues were concerned with a more realistic understanding of multi kilowatt power/thrust generation systems, means of coupling to the ambient space plasma and their consequences, and the types of radiation and noise that might be expected from a tether antenna system, including a better understanding of the propagation medium.

THURSDAY, 17 OCT 1985: The Electrodynamic Interactions working panel was broken into three subpanels in order to focus on the various issues identified on Wednesday. The three subpanels were:

1) Electrodynamic Tether Power and Thrust Generation Applications.
2) Space Experiments and Demonstrations.
3) ULF/ELF/VLF Antennas, Signal Generation and Detection.

The subpanels were instructed to meet and discuss issues pertinent to their specific areas, and to prepare written materials for presentation to the full working panel in the afternoon. One significant output of the Space Experiments and Demonstrations subpanel was the recommendation that a hollow cathode be flown as a plasma contactor on the Shuttle end of the upcoming TSS-1 experiment. That recommendation is included verbatum in the first appendix to this summary.

The remainder of this document is an integrated summary of Electrodynamic Interactions working panel results. This integrated summary is broken into three parts entitled:

1) List of Applications
2) Issues and Concerns
3) Flight Demonstrations

Each part incorporates output from the three subpanels which were convened on Thursday.

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II. LIST OF APPLICATIONS

Four areas of applications for electrodynamic tethers were identified by the Electrodynamic Interactions working panel:

1) MULTIKILOWATT TO MEGAWATT POWER AND THRUST GENERATION: In the 1 to 20 kilowatt power range, recommendations were made to use electrodynamic tethers to provide contingency power for the Space Station, and to provide drag makeup and orbital maneuvering capability for Space Station and other solar array powered satellites, or for the power extension package (PEP) which could then be left in LEO orbit between successive Shuttle flights. (Orbital maintenance of the PEP by the electrodynamic tether during these periods would require only a few percent of the overall solar array power output capability.) Collection of current from the ambient space plasma might be accomplished with a passive collector in a low power system, or with a hollow cathode device, exploiting the low current regime of this device ($i \leq 3$ amp). In the higher power ranges, up to approximately one megawatt, recommendations were made for a Space Station energy storage system, short term high power applications and orbital maneuvering of the Space Station or other large space systems. Success in these areas is considered contingent upon the successful operation of hollow cathodes or related devices acting as plasma contactors (active collectors) with minimum loss. Early demonstration of device performance capability is an important component in the overall development of the electrodynamic tether.

2) ELECTRODYNAMIC TETHER ULF/ELF/VLF ANTENNA: Ground based detection of electromagnetic emissions from a tethered satellite system is an area of interest to communications in the ULF/ELF/VLF frequency ranges. Sufficient energy available at the receiver is necessary for the operation of any communications system in the presence of background noise. Energy transmission factors, however, are presently insufficient to evaluate or optimize receiving system designs, particularly when advanced signal processing techniques are required. In order to estimate signal detectability at the receiver, information concerning signal characteristics (the transmitter), boundaries and propagation conditions (the medium), background noise statistical structure (in proximity to the receiver), and receiver characteristics are needed. Additionally, more advanced mathematical models than those presently in use are required for an adequate theoretical understanding of tether antenna systems.

3. OUTER PLANETARY MISSIONS

a.) JUPITER INNER MAGNETOSPHERIC MANEUVERING VEHICLE: The recommendation in this area was for a Jupiter inner magnetospheric survey platform to operate in the range from one to six Jovian radii. The electrodynamic tether in this application would be used primarily for orbital maneuvering operations.

b.) OTHER MISSIONS: Essentially, this area is an extension of the previous one to such regimes as exploration of the Saturn ring system, and beyond.

III. ISSUES AND CONCERNS

Three major areas were identified in this category by the Electrodynamic Interactions working panel, each listing a number of specific concerns:

1) MULTIKILOWATT TO MEGAWATT POWER AND THRUST GENERATION: The electrodynamic tether concept has grown to the point where a more realistic identification and evaluation of performance parameters of a high power and thrust generation system, and the environmental interactions induced by the operation of such a system, are now required. Specifically, the working panel made recommendations to:

   - Obtain voltage-current characteristics of plasma contactor devices operating at high tether currents (up to 50 amps).
   - Identify and understand the instabilities associated with such operations and their effects upon overall system performance.
   - Better understand the ionospheric/magnetospheric current closure path and its associated losses.
   - Understand what effects operation of a large electrodynamic tether power/thrust generation system will produce in the LEO environment, and what impact these effects will have upon other space vehicles.
   - Assure long term tether insulator survival.
   - Understand the effects of current collection at tether insulator defects and their overall impacts on system performance.

In addition to making these recommendations, a number of design tradeoffs, which need to be considered for designing an optimum electrodynamic tether system, were identified including:

- Shorter tethers operating at low voltage and high current might have advantages over longer tethers operating at high voltage and low current.
- Cable configuration:
  - Multiple cables connected in parallel (ribbon arrangements) might be preferable to single cables both in terms of length considerations (previous bullet) and in terms of resistance to damage by space debris (cable redundancy).
- Dynamics and control:
  - Counterbalancing tethers might be deployed in opposite directions from a spacecraft to provide center-of-mass-location control.
  - i 1 x B forces might be used for libration control provided that current phasing is correct.

- Power management, control and protection:
  - The electrical/electronic interface between the high voltage end of the tether and the user bus needs to be defined. This interface will contain all necessary power management, regulation and protection hardware, including the capability of switching the tether into and out of the system.

2. ELECTRODYNAMIC TETHER ULF/ELF/VLF ANTENNA: A number of concerns related to a basic understanding of a tether antenna system were identified. Specifically, the working panel made recommendations to:

- Characterize the propagation media including:
  - The ionosphere at LEO attitudes
  - The lower atmosphere
  - Ocean water (if submarine communication is the objective).

- Analyze sources of background noise and the statistical structure of that noise at the receiver.

- Determine ground station locations for best signal-to-noise ratio transmissions including the possibility of mobile receivers.

- Correlate signals received at different ground station locations in order to subtract off noise.

- Characterize the instabilities and waves due to large current densities in the Alfven wings.

- Begin using warm plasma theory in analytical work.
  - Cold plasma theory, although not always directly applicable, has been used to date because it is more easily handled.
  - Warm plasma theory is more appropriate to the analytical and numerical work, but is far more difficult to handle than cold plasma theory. Additionally, use of warm plasma theory places greater demands on computer time.
  - There is a need to supersede the present cold plasma based models with more accurate warm plasma based models.

3. HOLLOW CATHODES AND ELECTRON GUNS - COMPARISON AND ISSUES: In order for the electrodynamic tether power/thrust generation concept to be viable, it is necessary to make electrical contact with the ionsphere at both ends of the tether. Contact may be made in a number of ways including use of a passive, conducting subsatellite (as is the case with TSS-1), use of an electron gun, or use of a plasma generator (such as a hollow cathode or hollow cathode based device). If operated within the range of its current carrying capability, the plasma generator will function in such a manner as to "ground" the spacecraft or subsatellite of which it is part very nearly to the local plasma potential (within a few volts), independent of the current flowing through it. This feature has the advantage of establishing a known satellite ground reference potential with respect to the local plasma to which probe or particle energy measurements may then be referred. Using an electron gun does not establish such a known ground

reference; rather, the gun will operate in a more or less constant current mode which is essentially independent of the operating voltage and will permit the satellite potential to vary considerably with respect to the local plasma potential. The working panel concentrated on hollow cathode type plasma generator devices and specifically made recommendations to:

- o Perform laboratory and analytical characterization of plasma diffusion, double sheaths, magnetic field effects and contact impedance.
- o Develop a high current plasma contactor technology with electron currents up to 50 amps and ion currents up to 2 amps.
- o Fly a hollow cathode on the Shuttle Orbiter for the TSS-1 mission (see appendix).
- o Fly hollow cathode based plasma contactors on both ends of the tether for future TSS electrodynamic missions.

IV. FLIGHT DEMONSTRATIONS AND APPLICATIONS

Three areas of flight demonstration were identified by the Electrodynamic Interactions working panel:

1) PLASMA MOTOR GENERATOR PROOF OF FUNCTION (POF) FLIGHTS: Three candidate missions were identified in this area in order to explore hollow cathode versus passive electron collection from the ionosphere, il x B deflections of the tether, use of tether ballast with a simple deployer and high current delta-V dynamics. The first mission involves use of a 200 m conducting tether with hollow cathodes at both ends of the tether, a variable biasing capability and currents no more than 0.1 amp. The hollow cathode collector in this mission will be operated in both an active and a passive mode so that comparisons may be made between the two modes. The second mission involves use of a 2 km tether with hollow cathode based plasma contactors at both ends and currents up to 5 amps. A simple deployer with a ballast tether will be used in this mission, and i l x B dynamics of the electrodynamic tether will be explored. The third mission involves a 10 km tether with hollow cathode based plasma contactors at both ends operating at currents up to 50 amps. This mission will explore high current delta-V dynamics and orbital maneuvering via electrodynamic thrust generation.

2) CHOICE OF EARLY MISSIONS: The missions in this area will use electrodynamically generated power levels of 1 to 20 kilowatts, and will demonstrate capability for drag makeup and orbital maneuvering of Space Station and other large space systems.

3) LONGER TERM MISSIONS: The missions in this area will use electrodynamic power levels up to one megawatt with ULF/ELF/VLF antenna applications and planetary missions in mind.

V. CONCLUSION:

The Electrodynamic Interactions working panel, in its two days of intensive meetings, focused on issues involving electrodynamic power and thrust generation applications, space experiments and demonstrations, and electrodynamic tether antenna signal generation and detection. Applications were identified in the areas of:

- Multikilowatt to megawatt power/thrust generation.
- Communications.
- Planetary exploration.

Additionally, many issues and concerns were identified in each area including:

- Hardware characterization.
- Environmental interactions and characterization.
- Design tradeoffs.
- Development of better models and theories.

A unanimous recommendation was drafted to fly a hollow cathode on the Shuttle Orbiter as part of the upcoming TSS-1 mission. (See Appendix.)

Finally, a number of short and long term flight demonstrations and applications were identified including:

- Early proof of function flights.
- Low impedance current collection by means of hollow cathode or hollow cathode based plasma sources.
- Drag makeup and orbital maneuvering of Space Station and other large space systems.
- Multikilowatt to megawatt power generation.
- ULF/ELF/VLF antenna applications.
- Planetary exploration to include the Jovian magnetosphere and Saturn ring system.

APPENDIX-1

RECOMMENDATION FOR TSS-1 MISSION

1. A plasma contactor should be provided on the Orbiter carrying the TSS-1 experiment. It should be operated:

   a) To demonstrate this critical contactor technology which is needed for effective electrodynamic tether operation;

   b) Ensure that the Orbiter is clamped at a potential near local space plasma potential; this should ensure proper operation of the electron generator and facilitate measurement of the ejected electron energy;

   c) To prevent unintentional, differential, high voltage charging of Orbiter surfaces.

2) A hollow cathode device is recommended as the plasma contactor on the Orbiter for the TSS-1 mission.

APPENDIX-2

Orbiter Ion Collection Calculations Using NASCAP/LEO

Myron Mandell and Ira Katz
S-CUBED, A Division of Maxwell Laboratories

Calculations of the collection of ion currents by the shuttle orbiter were performed using the *NASCAP/LEO* code. *NASCAP/LEO* models in three dimensions the plasma around the the orbiter. For these calculations most of the computational space was zoned to 1.27 meter resolution, with the main engine area zoned to 0.635 meter resolution. The calculations include thermal ion distribution and velocity effects. For each ground potential, a Poisson calculation was followed by a particle trajectory calculation. The ion current collected consists of those ions which land on the engine housings. The projected area of the engine housings was 22.4 m^2 for each of the three main engines, and 0.4 m^2 for each of the two OMS engines, totalling 68 m^2 of conductive area.

Calculations were run with the engines facing the ram direction (ram position), with the wingspan parallel to the ram direction (sideways position), and with the engines in the wake of the shuttle body and wingspan (wake position). The ion species was taken to be atomic oxygen, and plasma densities of 10^5 cm^{-3} and 10^6 cm^{-3} were used. The plasma temperature was taken as 0.1 eV. Results for six logarithmically spaced voltages are shown in tables 1-3. A few example calculations indicate that magnetic field effects are insignificant for ion trajectories; if they have any effect, it is to decrease the collection. The collected currents are also reasonably insensitive to the amount of conductive area on the engines. For example, at a potential of -3000 volts and density 10^6 cm^{-3} a conductive area of 10.4 m^2 collected 0.19 amperes, while 96 m^2 collected 0.41 amperes.

From a previous study, we have approximate current values (table 4) for electron collection by the sphere, including magnetic field limiting. The currents in table 4 should be considered as realistic lower bounds; to the extent that true currents are higher, the shuttle will be driven more negative than we are about to calculate. The EMF generated by the tether is equal to the difference between the sphere potential and the orbiter potential, plus the resistive voltage drop across the tether. Taking the EMF to be 4000 volts, the tether resistance to be 2000 ohms, and the plasma density 10^6 cm^{-3}, we estimate from tables 1-4 (table 5) that the orbiter will commonly achieve negative potentials in excess of 2000 volts. This conclusion is based on magnetic field limiting of electron current; if electron collection is not dominated by magnetic fields, the sphere voltage would drop by about half, with a corresponding increase in the (negative) orbiter potential.

Table 1.

Ram Position - 68 m^2 Conducting Area

Voltage	$I(10^5\ cm^{-3})$	$I(10^6\ cm^{-3})$
-10	0.006	0.059
-30	0.007	0.063
-100	0.009	0.075
-300	0.017	0.108
-1000	0.034	0.212
-3000	0.057	0.341

Table 2.

Sideways Position - 68 m^2 Conducting Area
[Wing to Ram]

Voltage	$I(10^5\ cm^{-3})$	$I(10^6\ cm^{-3})$
-10	0.0043	0.043
-30	0.0045	0.044
-100	0.0057	0.046
-300	0.0119	0.065
-1000	0.0272	0.156
-3000	0.0455	0.284

Table 3.

Wake Position - 68 m^2 Conducting Area

Voltage	$I(10^5\ cm^{-3})$	$I(10^6\ cm^{-3})$
-10	0.0006	0.005
-30	0.0015	0.011
-100	0.0031	0.018
-300	0.0085	0.039
-1000	0.0213	0.109
-3000	0.0424	0.228

Table 4.

Electron Collection by Sphere

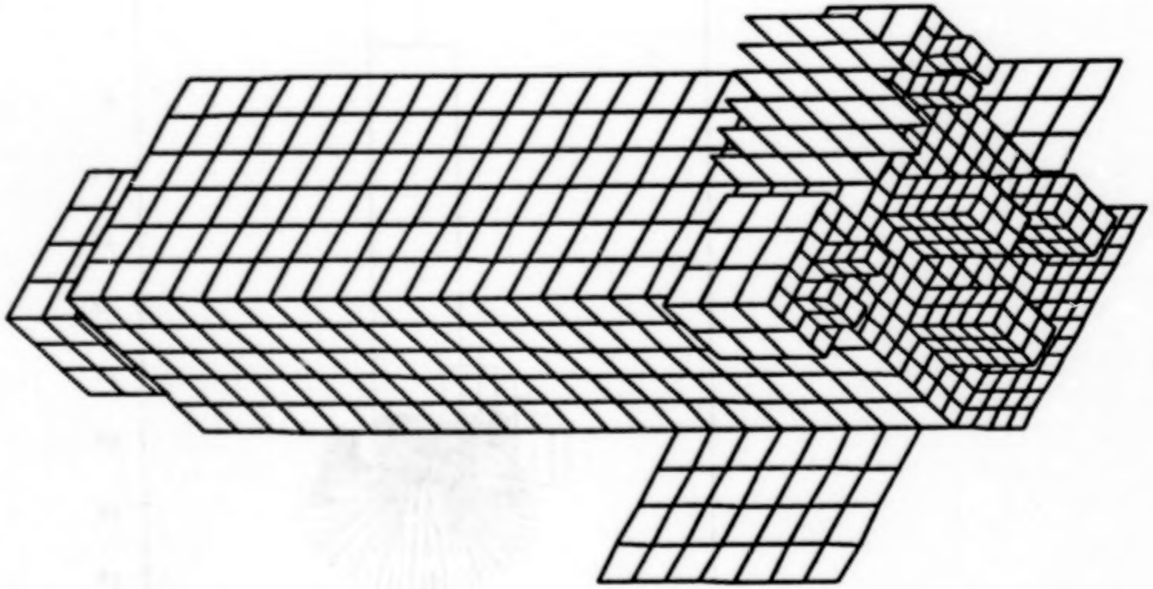
Sphere Potential [Volts]	$I(n_e=10^6\ cm^{-3})$ [Amps]
500	0.16
1000	0.22
2000	0.30
4000	0.41

Table 5.

Orbiter-Sphere Floating Potentials at $10^6\ cm^{-3}$

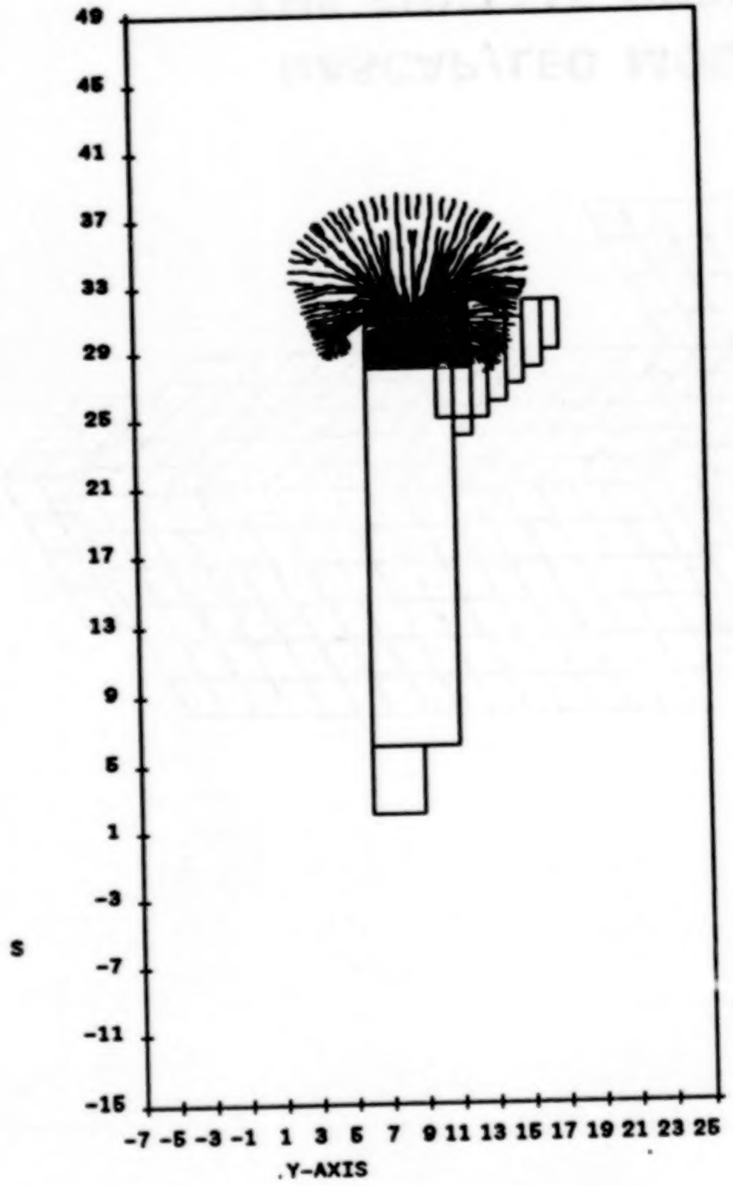
Position	Sphere Potential [Volts]	Orbiter Potential [Volts]	Tether Current [Amperes]
Ram	1500	-2000	.26
Sideways	1000	-2600	.22
Wake	800	-2800	.20

C-5



NASCAP/LEO MODEL
THE SHUTTLE ORBITER

PARTICLE TRAJECTORIES PROJECTED INTO THE Y-Z PLANE



Subcommittee on Electrodynamic Applications

ELECTRODYNAMIC TETHER POWER AND THRUST GENERATION APPLICATIONS

J. McCoy	JSC
S. Martinez	MIT
F. Kelley	NRL

ISSUES:	RECOMMENDATIONS:
Experiments/Demonstrations	- Plasma-motor generator proof-of-function (P.O.F.) flights: (I) 200 m, hollow cathode/passive, $I < 0.1$A (II) 2 km, H.C. at $I \sim 5$A. $\vec{I} \times \bar{B}$ deflection. Use of tether ballast (simple deployer) (III) 10 km, H.C. at $I \sim 50$A. Explore high I-ΔV, dynamics - TSS-1 Restore hollow cathode to core equipment - TSS-1 study wave generation/detection - TSS-1 Provide H.C. at both ends of tether A.S.A.P.
Choice of Early Missions	- 1 to 10/20 kW range Look at low power system with passive collector Exploit low current H.C. regime ($I \lesssim 3$ A) - Drag make-up of PEP, other S.A. powered satellites - Orbital maneuvering of above - Space Station drag make-up - Contingency power for Space Station - Look for other potential users
Candidate Longer-Term Missions	- Up to ~1 MW - Contingent upon hollow cathode or other low-loss contactors demonstrating performance - Space Station power storage system - Orbital maneuvering of Space Station or other large satellites

- Short-term, high power applications
- Look for other PMG users
- VLF-ELF applications
- Jupiter inner-magnetosphere (1-G R_J) orbital maneuvering and low-altitude survey platform
- Other planetary missions

Critical Technical Questions:

- V-I Performance of Plasma Contactors at High I	- P.O.F. tests Theoretical effort
- Current Closure Losses	- Uses P.O.F. tests to measure path impedance - continue analytical efforts - Analyze TSS-1 data at maximum current
- Onset of Plasma Instabilities	- Analytical work to estimate thresholds Analytical work to predict EM noise Analytical work to predict extra losses TSS-1 data at maximum current
- Effect on Environment and Other Vehicles	- Analysis of wake/wings. Use steady reference frame TSS-1 data
- S/N Ratio of Various Wave Modes	

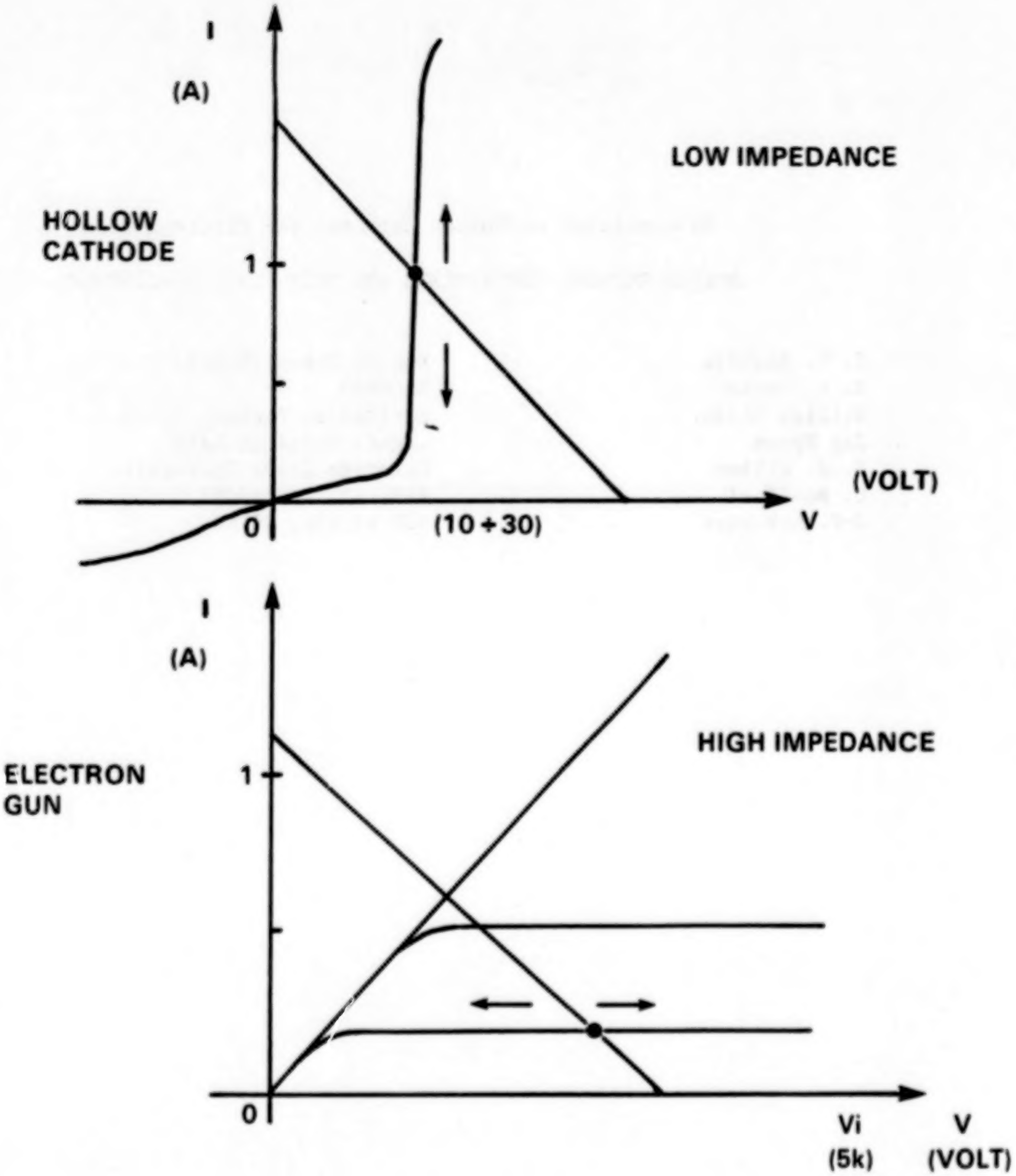
Design Optimization Questions:

- Tether Length	- As short as allowed by contactor current capabilities Study tradeoffs (contactor ΔV vs. wire resistance, insulator savings vs. need to ballast, effects of short closure path)
- Cable Configuration/ Materials	- Single vs. multiple cable (debris effects, reliability, cooling, insulator mass, deployment ...) - Cylindrical vs. tape conductor, stranding - Materials for long-term operation
- Dynamics and Control	- Use passive ballasting tether to provide tension Study dynamics/control of unballasted and ballasted configurations - Study impact of dynamic delays (on-off, power-thrust, current/power modulation ...)
- Power Management	- Impedance matching/variation Inversion/regulation/switching Desirable V,Ω levels

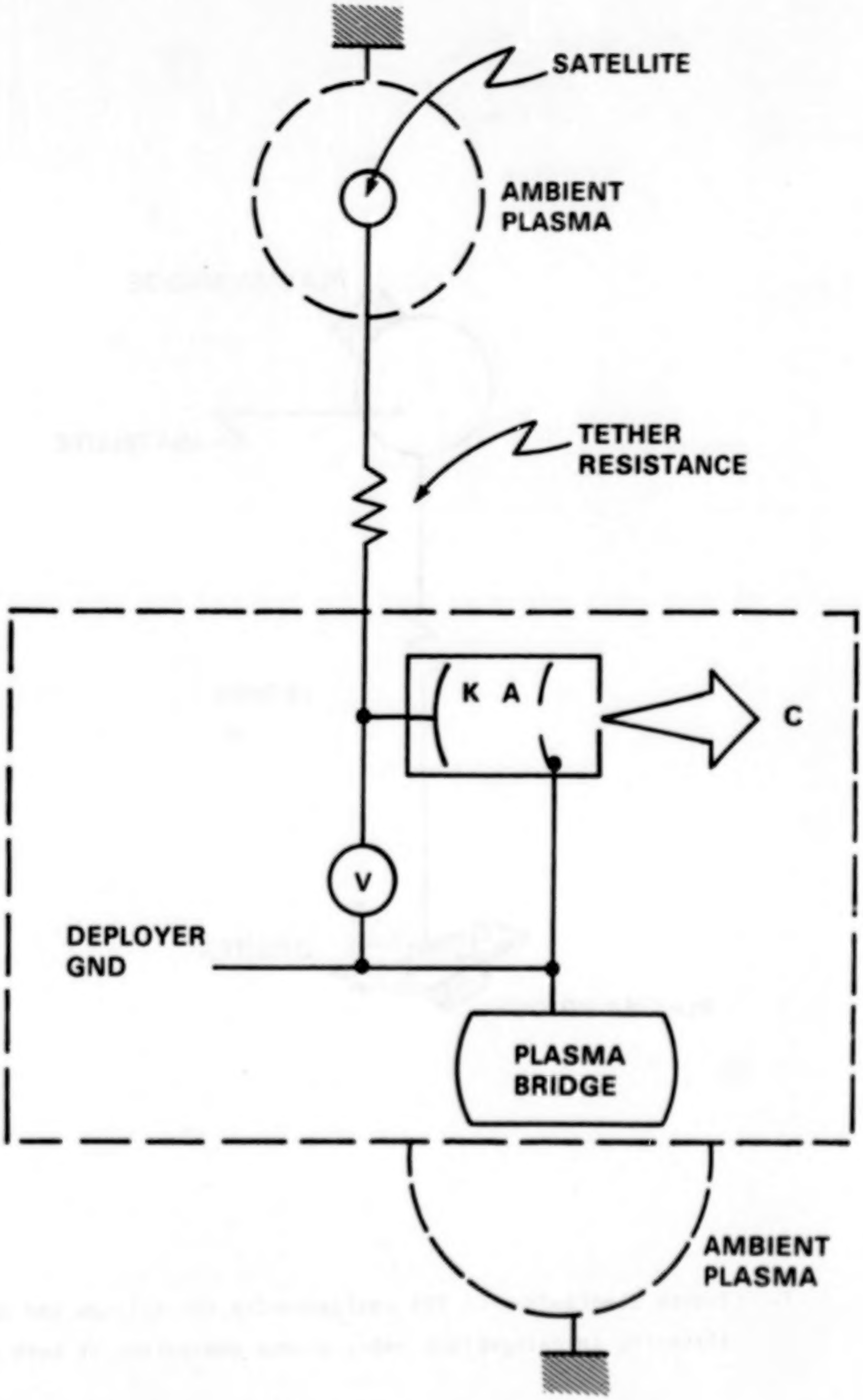
Subcommittee on Hollow Cathodes and Electron Guns

HOLLOW CATHODE EXPERIMENTS AND TECHNOLOGY DEVELOPMENTS

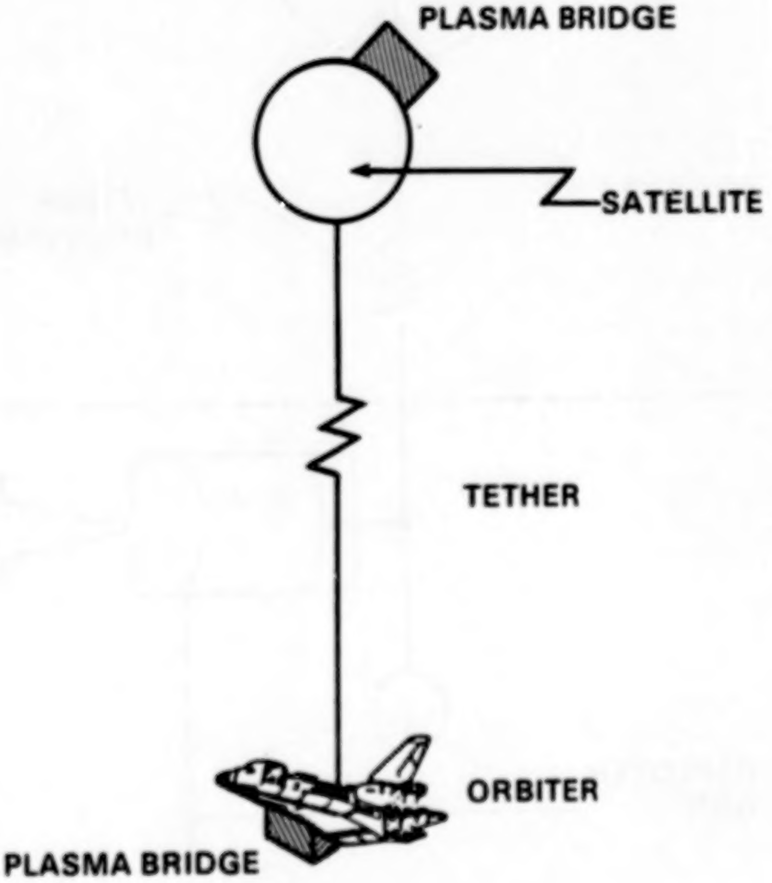
J. R. Beattie	Hughes Research Labs
D. E. Parks	S-CUBED
William Miller	Aeritalia, Torino, Italy
Jay Hyman	Hughes Research Labs
P. J. Wilbur	Colorado State University
C. Bonifazi	PSN/CNR; IFSJ-/CNR
J-P. Lebreton	SSD of ESA, ESTEC



1. Top, I-V typical characteristics of a Hollow Cathode
Bottom, Electron Gun characteristics. This information shows that electron guns may be operated in a constant current mode independantly of voltage whereas the hollow cathode may be operated in a constant voltage mode essentially independent of current. Thus, use of a hollow cathode, or more generally, a plasma generator, provides a ground "strap" tying the spacecraft to the local plasma potential.


SATELLITE
AMBIENT PLASMA
TETHER RESISTANCE
K
A
C
V
DEPLOYER GND
PLASMA BRIDGE
AMBIENT PLASMA

2. Electrodynamic TSS (Tethered Satellite System) functional configuration for basic science experiments, showing where the plasma contactor (bridge) is operating.

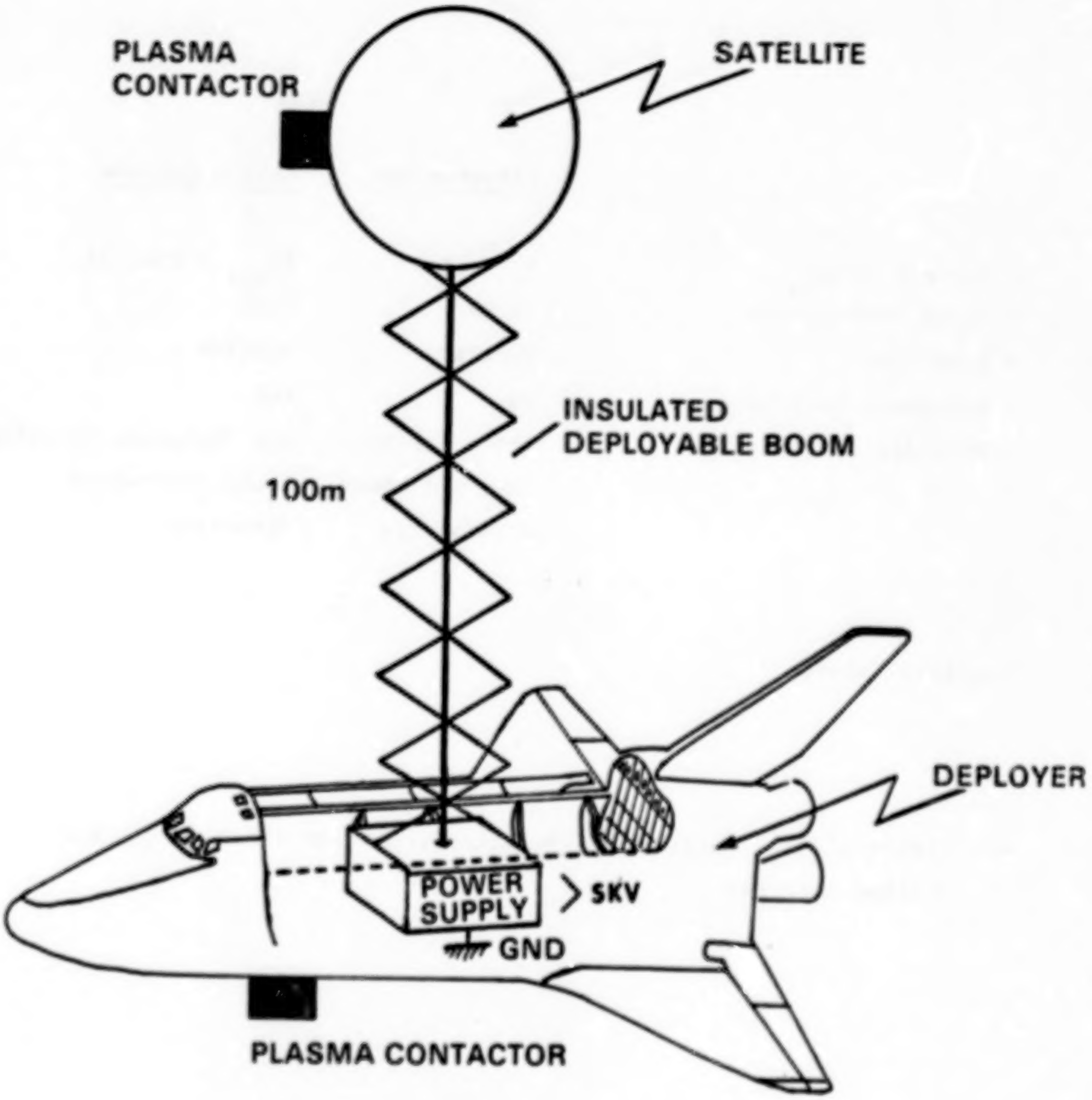

PLASMA BRIDGE
SATELLITE
TETHER
ORBITER
PLASMA BRIDGE

3. Future electrodynamic TSS configuration for science and power/thrusting investigations using plasma generators at both ends.

	Electron Gun	Hollow Cathode
- Current Range:	$I_e \overset{\sim}{<} 1A$	*$I_{e,i} > 10A, 1A$
- Power Consumption	~1 kW	~10W
- Life Time:	Similar	Similar
- Automatic Switching	No	Yes
- Main Applications	Basic Science Exp. and Power Dissipation	Low Impedance Coupling Power Generation Thrusting

*Nominal Values

4. Table of main comparative characteristics for electron gun and hollow cathode.


PLASMA CONTACTOR
SATELLITE
INSULATED DEPLOYABLE BOOM
100m
DEPLOYER
POWER SUPPLY
> 5KV
GND
PLASMA CONTACTOR

5. Recommendations for a plasma contactor space experiment. A biased sphere is deployed on a 100 m insulated boom with plasma generators at both ends. This experiment measures current capabilities with the plasma generators on and off, and allows for additional diagnostics as well. It can also be duplicated in ground vacuum chamber experiments allowing for a correlation between ground and space tests.

Continued Technology Development

- Laboratory Investigations
  - Evaluate plasma contactor performance in simulated, well-characterized space plasma
  - Include magnetic field effects
  - Support development of theoretical model
    - plasma diffusion
    - double sheath
    - magnetic field effects
    - contact impedance
  - Develop high-current plasma-contactor technology (J_e~50 A, J_i~ 2A)
  - Current collection at tether insulation defects

- Theoretical Models
  - Include magnetic field effects in fluid flow model
  - Leakage current collection at tether insulation defects
  - Impedance model for electron emission, electron collection by plasma contactors

Appendix to Hollow Cathode Experiments and Technology Development Section

Recommendation for TSS-1 Mission

1. A plasma contactor should be provided on the Orbiter carrying the TSS-1 experiment. It should be operated:

   a) to demonstrate this critical contactor technology which is needed for effective electrodynamic tether operation;

   b) to ensure that the Orbiter is clamped at a potential near local space plasma potential; this should ensure proper operation of the electron generator and facilitate measurement of the ejected electron energy; and

   c) to prevent unintentional, differential, high voltage charging of Orbiter surfaces.

2. A hollow cathode device is recommended as the plasma contactor on the Orbiter for the TSS-1 mission.

Subcommittee on Tether Antennas

USE OF ELECTRODYNAMIC TETHERS AS ULF/ELF ANTENNAS

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G. Tacconi	**University of Genova, Italy**

EM radiation from the tether - outstanding theoretical problems:

(1) Warm plasma effects have not yet been fully considered - new modes?

$$\nu_A = \nu_{Te}$$

(2) Plasma instabilities and wave generation due to high current densities in the Alfven wings

(3) Transmission of various types of waves through the ionosphere - electrostatic wave mode conversion?

(4) Radiation from oscillating tether current taking into account the total tether/ionosphere system, including (1) - (3)

TSS-1 ground station ELF/ULF detection optimization

(1) Theoretical definition of emitted signal characteristics

(2) Analysis of background noise statistical structure

Optimum Processing

(3) Use of space correlation (if confirmed by theory)
  - one receiver in "hot spot", another outside

(4) Site selection for maximum signal and minimum noise
  - mobile receivers to be used

(5) Night time reception

Tether Radiation Experiments

(1) The tether current should be oscillated at frequencies throughout the ELF/ULF/VLF band.

(2) The flight profile should be chosen to fly over ground-based Thompson scatter observatories (Arecibo, Jamaica, etc.) to provide detailed knowledge of the ionospheric F, E, and D-layers in the region of the tether radiator.

(3) Data from F-layer monitor network must be examined for evidence of travelling ionospheric disturbances in the tether region.

(4) January flights would be optimal from the standpoint of lowest ELF receiver site noise and least disturbance of the tether's ambient electrical and magnetic conditions.

The Tether as an Antenna

(1) Basic linear theoretical studies predict that large electric dipole or loop antennas in space with sufficient power (~1 kW to multi-MW) can produce detectable and usable signals on the Earth's surface.

(2) Non-linearities might degrade the conversion from tether power to propagating signal power. These non-linearities need to be studied in detail, both experimentally and theoretically.

(3) Theoretical studies suggest that large array antennas might suppress unwanted radiation into loss cones of the index of refraction surface. Can practical configurations be devised that are highly directional?

ELECTRODYNAMIC INTERACTIONS PRIORITIES

Summary of 18 October 1985 Meeting of Panel Co-Chairmen

TSS Era

- Proof of function (POF) of hollow cathodes (and hollow cathode based plasma contactors) in the LEO environment at milliampere to ampere levels of current collection from the ambient magnetoplasma.
  - Hitchhiker-G and early POF flights.
  - Possible use of a hollow cathode device on TSS-1.

- Electrodynamic Tether Power and Thrust Generation
  - Multiampere $i \hat{l} \times B$ deflection for dynamic control of tether. (Current levels on the order of 5 amp.)
  - Multiampere operations to explore high current ΔV dynamics. (Current levels on the order of 50 amp.)

- Identification of system requirements for higher power (multikilowatt) operations.
  - Power management and control/interface between high voltage end of tether and user.
  - Identification of necessary technologies and technology developments to meet the needs.

Space Station Era

- Electrodynamic operation in the 1 to 20 kW range.

- Use of electrodynamic tether thrust generation for drag makeup in PEP and other solar array powered satellites.

- Use of electrodynamic tether thrust generation for orbital maneuvering.

- Space Station related activities:
  - Drag makeup
  - Contingency power

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- Continued development of those technologies needed for progressively more advanced operations.

and Beyond . . .

- Electrodynamic power generation in the high kilowatt to megawatt range.

- Orbital maneuvering of Space Station and/or other large space systems.

- ULF/VLF/ELF electrodynamic tether antenna applications.

- Planetary missions (such as exploration of Jovian inner magnetosphere, Saturnian ring system, etc.).

N86-28425

LABORATORY SIMULATION OF THE ELECTRODYNAMIC INTERACTIONS OF A TETHERED SATELLITE WITH AN IONOSPHERIC PLASMA

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ABSTRACT

An improved experimental set-up in the Orleans Plasma Chamber (Lebreton et al., 1985) allowed investigations of the I-V characteristics of a conductive spherical body (10 cm diameter) in a plasma environmemt. Moreover the influence of a transversal magnetic field at 0.6 and 1.2 G has been investigated, for the first time, both on the sheath potential profile and current collection. Floating potential profiles have been measured at 16 different radial distances from the test body up to 9 body radii in 8 different angular positions. The test body potential could be increased in the range from -200 V up to +100 V. Preliminary results are shown and discussed in this presentation.

1.0 INTRODUCTION

In the first electrodynamic mission of the Tethered Satellite System (TSS),beyond experiments involved with the Core Equipment (Bonifazi , this issue), particular studies should be carried out in order to study the interaction of a conductive body at high potential (up to + 5 kV) with respect to the surrounding ionospheric plasma (Dobrowolny,1985). Laboratory simulation of the interaction of a free flying satellite with the ionospheric plasma has been studied since the early sixties (Hall et al.,1964). A brief review of early laboratory investigations of bodies in flowing, rarefied plasmas is given by Stone (1981). Nevertheless the experimental conditions around the TSS will be different from those occuring around a fre flying satellite. To our knowledge, the only work with probes at high potential (up to 1000 V) in a plasma chamber is that of Kawashima (1982) which however refers to high magnetic fields (B = 500 G) and higher plasma densities (1.0E07 1.0E08 cm-3) with respect to those of the ionosphere at 250 km altitude (TSS). In a previous work (Lebreton et al., 1985) carried out with a less sophisticated set-up and without computer control, quite interesting results have been already shown for a test body of 10 cm diameter immersed in an omogeneous plasma at ionospheric densities (1.0E06 cm-3). Thus we will summarize here the experimental set-up, pointing out the modifications and improvements. The results here achieved are only described in a preliminary way since detailed data analysis and theoretical interpretation will follow in a more complete work.

2.0 EXPERIMENTAL SET-UP

Figures 1 and 2 show the experimental set-up in the Orleans Plasma Chamber. For more details see Lebreton et al.1985 and enclosed references. During our experiment the values obtained for plasma densities and electron temperatures correspond to typical values of the E- and F- regions of the ionosphere (see Table-1). An Ar-ion beam was produced by the ion source at 12 V acceleration potential in order to simulate the plasma impact velocity on the TSS (8 km/sec). The plasma confinement inside the vacuum chamber is achieved through a multipolar magnetic field system. The plasma potential obtained equals the potential of the vacuum chamber and a coils system allows the compensation of the Earth's magnetic field and the production of known field intensities up to a maximum of 1.2 G in axial or transversal direction with respect to the ion beam direction. The test body is situated in a fixed position inside the chamber (see figures 1 and 2) and is electrically connected with a power supply and an electrometer in order to obtain I-V characteristics in the range (-200 V, +100 V). A cross system consisting in 16 Langmuir probes (r=0.3 cm) situated at different distances from the test body from 0.2 to 9.4 test body radii can be rotated at 8 different angular positions. A total of 128 measurement points can be achieved in this way. A multiplexer time sharing, realized by means of high insulation resistance (1.0E12 Ohms) reed relais, allows the determination of I-V characteristics for each probe in a voltage range -10 V to 10 V. The power supplies connected to the test body, Langmuir probes position system and data acquisition are under computer control. The plasma characteristics were continuously monitored during the experiments by means of a reference spherical Langmuir probe and a mutual impedance probe located sideward at about one meter downstream from the test body. Table-1 shows experimental conditions compared with ionospheric ones.

3.0 EXPERIMENTAL RESULTS

3.1 Test body I-V characteristics

3.1.1 Negatively charged body

The current collected upon a conductive spherical body negatively polarized with respect to the ambient plasma, in an unmagnetized and in a magnetized plasma has been investigated during the first experiment (Lebreton et al., 1985). The I-V characteristic of a 10 cm diameter sphere has been measured under stable plasma conditions, quoted in table-1 under exp 1, for a test body potential ranging from 0 Volt up to - 125 Volt. The Ar-ion beam energy was 12 eV in order to simulate the TSS orbiting velocity of 8 km/s. An external magnetic field og 0.68 Gauss along the beam direction did not seem to modify the test body ion collection characteristic. This result has been interpreted as mainly due to the fact that Argon ion gyroradius was very large compared to the dimension of the test body. This result can still apply to the TSS satellite conditions during the first TSS electrodynamic mission. The same measurement has been repeated during the second experiment by using the same test body. In this case the test body potential has been extended up to - 200 Volt, and the magnetic field was transversal (0.6 and 1.2 Gauss) to the beam direction in order to simulate the TSS conditions. The result shown in figure 3 basically confirms that there is not magnetic field effect on ion collection upon a relatively highly polarized body immersed in a mesosonic plasma.

3.1.2 Positively charged body

The electron current collected upon a conductive sphere immersed in a mesosonic plasma has been investigated in presence of a magnetic field. The maximum positive potential of the test body is limited by the plasma source capability. For the Orleans plasma chamber this corresponds to a maximum electron current of about 10 mA upon a conductive sphere of 10 cm diameter. Diuring the first experiment (Lebreton et al., 1985) the I-V characteristic of the test body has been studied both in presence of no magnetic field and in presence of an axial (i.e., along the beam direction) external magnetic field. The plasma conditions are those quoted in Table-1 under the label exp 1. The measurements shown in figure 4 clearly indicate a reduction of a factor of two in the electron current collection in presence of an external magnetic field of 0.68 Gauss under the same plasma conditions for B=0 G. It is worth noting that no change in the plasma conditions have been detected during the two data sets. The plots shown in figure 4 have been corrected by the function Ne(Vp)/Ne(OV), where Ne(Vp) and Ne(OV) are respectively the electron density measured when the test body potential is Vp and 0 Volts.

The electron thermal current has been estimated by the relations:

(1) Ieo = 1/4 Ne e Vth A

and

(2) Ieo = 1/8 Ne Vth A

where Ne is the electron density, Vth the electron thermal velocity, e the unit charge, and A the geometrical area of the test body. The difference between relation (1) and (2) is a factor of two due to the channeling effect of the magnetic field. The electron gyroradius based on plasma conditions quoted in Table-1 results in 1.6 cm and satisfies the condition: electron gyroradius less than test body radius. No carefully test of the to date avaible models has been carried out. Nevertheless it worth noting that the model by Linson et al. (1982) foresees an electron current reduction of a factor of two when the effect of an external magnetic field has been taken into account. The paper by Linson considers a magnetic fild aligned along the ion beam direction as we had during the first experiment.

During the second experiment the effect of a transversal magnetic field has been investigated for the first time. The plasma conditions are quoted in Table-1 under label exp 2. The reason to have a transversal magnetic field is that of simulate TSS satellite enviromental conditions. In fact the induced emf across the TSS is V X B, where V is the TSS orbiting velocity. We report here the preliminary results obtained by using the same test body of the first experiment. The electron current versus sphere potential for respectively 0 G, 0.6 G, and 1.2 G are shown in figure 4 or a test body potential ranging from zero up to 100

Volts. The plasma conditions were Ne = 1.6E06 cm-3, Te = 0.16 eV which yield to an electron gyroradius of 2.5 cm (B=0.6 G) and 1.25 cm (b= 1.2 G), respectively. In both cases the electron gyroradius is less than the test body radius. The electron thermal currents estimated by relations (1) and (2) yield Ieo =336 micro A (B=0), and Ieo = 168 micro A (B=0.6 and B=1.2 G). The plots shown in figure 5 are corrected by the function Ne(Vp)/Ne(OV) as for figure 4. The plasma density variations versus test body potential during the second experiment are quoted in Table-2. The electron density has been measured by a mutual impedance probe and by a reference Langmuir probe. The trend of the electron current versus test body potential in presence of a transversal magnetic field clearly confirms the reduction of the electron current previuously observed in presence of an axial magnetic field (see figure 4). Moreover higher magnetic fields seem to produce greater reduction of electron collection.

3.3 Sheath and near-sheath potential profile.

The sheath and near-sheath potential profile has been explored in 2 directions along the plasma flow : the upstream (ram) and the downstream (wake) directions.

This has been done only for negatively polarized test body during the first experiment (Lebreton et al. 1985). Two identical cylindrical Langmuir probes,spaced by 10 cm. along the radial direction, where translated at distances up to 25 cm. from the test body surface.

The floating potential contour upstram and downstream of a negatively polarized test body,under the same plasma condictions of fig.4 ,are shown in fig.6 . The test body potential is -125 Volt and measurements without magnetic field and with B=0.6 G along the Ar+ ion beam direction are compared in the figure.

The effect of an external magnetic field does not seem to modify the shape of the upstream sheath region but only the shape of the wake region.

The upstream region extends up to 3 times the test body radius and the floating ptential of the probes reduces to 1-2% of the central body potentialat 1.2 test body radii.

The wake region extends up to 5 test body radii without magnetic field and reduces to 3 test body radii when B=0.6 G. At larger distances the floating potential is still offset by a few volt when compared to the unperturbed plasma potential which is very close to zero.

The floating potential of the probes reduces to 1-2% of the test body potential at 2.5 (B=0) and 3.0 (B=0) test body radii.

We should not attempt to interpret floating probe potential measurements in term of plasma potential since the floating potential may be very sensitive to a small change in the ion density or electron temperature , more precisely in the hot electrons flux (Lebreton et al. 1985).

The space charge region investigation has been carried out during the second experiment in the Orleans plasma chamber by using a more sophisticated set-up described in section 2. Unfortunately we are not able to show the measurements but only a typical output of the sixteen spherical Langmuir probes (radius 0.15 cm.),see fig.7, which allows investigation of the sheath in the range distance from 0.2 up to 9.4 test body radii.

This extension in the explored region should allow more detailed investigation of the wake region ,moreover in this case the space charge region exploration was not limited to the ram and wake directions but extended to 8 angular position over the 360 degrees region.

4.0 CONCLUSIONS

In a plasma chamber reproducing the electrodynamic tethered satellite environmental condictions (see Table -1-), we have measured the I-V characterist of a spherical conductive test body of 10 cm. diameter and explored its sheath and near sheath regions.

This investigation has been carried out through two successive experimental set-ups .

The main results can be summarized as follow :

the presence of an axial magnetic field of 0.68 G reduces by a factor about 2 the electron current collected upon the test body, but not the ion current, when the test body potential varies from -125 V up to +50 V .

This investigation has been repeated by extending the test body potential range from -200 V up to +100 V and using a transversal magnetic field of 0.6 G and 1.2 G, respectively.

These measurements pratically confirm the previous results and clearly indicate a decreasing of the electron current collection for increasing magnetic fields.

The investigation of the sheath and near-sheath around the test body up to about 10 test body radii in 8 different angular position over the 360 degrees field will be reported in a future paper now in progress.

FIGURE CAPTIONS

FIG.1

Set-up of the first experiment. A spherical conductive body of 10 cm diameter is located at the centrum of the Orlens plasma chamber. LP are the cylindrical Langmuir probes by which the plasma parameters are continuously monitored (LP) at the bottom of the chamber, and the floating potential contours around the test body can be measured, the two LP which can be radially translated and rotated by remote control with respect to the sphere.

FIG.2

Set-up of the second experiment. The same test body of the first experiment is located at the centrum of the Orleans plasma chamber. At the right-hand upper corner is shown the mutual impedance probe by which the plasma parameters are continuously monitored. At the left-hand upper corner is shown the Langmuir probe of reference for plasma parameters monitoring. At the bottom is shown the cross system on which the 16 Langmuir probes are located up to radial distances of 9 test body radii.

FIG.3

Ion current collection versus test body potential under plasma conditions quoted in Table-1 under label exp 2. The black dots refer to a zero magnetic field, while the triangles and squares to a transversal magnetic field of 0.6 and 1.2 Gauss, respectively.

FIG.4

Electron current collected under plasma conditions quoted in Table-1 under label exp 1. The upper curve refers to a zero magnetic field while the lower curve to an axial magnetic field of 0.68 Gauss.

FIG.5

Electron current collected upon a 10 cm diameter sphere under plasma conditions quoted in Table-1 under label exp 2. The black dots, triangles, and squares refer to zero, 0.6 G, and 1.2 G transversal magnetic field, respectively.

FIG.6

Floating potential contours upstream and downstream a negatively polarized test body under the plasma conditions quoted in Table-1 under label exp 1.

FIG.7

Example of the I-V characteristics of the 16 Langmuir probes located radially with respect to the test body. Each Langmuir probe characteristic is plotted in log ang linear scale for a potential range from -10 V to 10 V.

ACKNOWLEDGEMENTS

We are grateful to the following people for their technical help before and during the experiments: G. Ferri, E. Rossi, P. Frot, and M. Smargiassi for his software support.

REFERENCES

- Lebreton, J.P., Bonifazi C. et al.,"Laboratory Simulation of Electrodynamic Interaction of the Tethered Satellite with Ionosphere"
  ESA-SP-229, 221, 1985

- Bonifazi, C., "Tethered Satellite System (TSS) Core equipment"
  This issue

- Dobrowolny, M.,"The Tethered Satellite System project "
  ESA-SP-229, 211, 1985

- Hall, D.H., Keng, R.F. and Sellen, J.M.,"Plasma Vehicle Interaction in a Plasma Stream"
  AIAA Journal, Vol. 2 (6), 1032, 1964

- Kawashima, N.,"Experimental Studies of the Neutralization of a Charged Vehicle in Space and in Laboratory in Japan"
  Artificial Particle Beams in Space Plasma Studies
  NATO Advanced Study Institutes Series, Plenum 1982

- Stone,N.h.,Samir,U., "Bodies in flowing plamas: Laboratory studies"
  Adv. Space Res. Vol.1, 361, COSPAR

- Linson, M.L.,"Charge Neutralization as Studied experimentally and Theoretically"
  Artificial Particle Beams in Space Plasma Studies
  NATO Advanced Study Institutes Series, Plenum 1982

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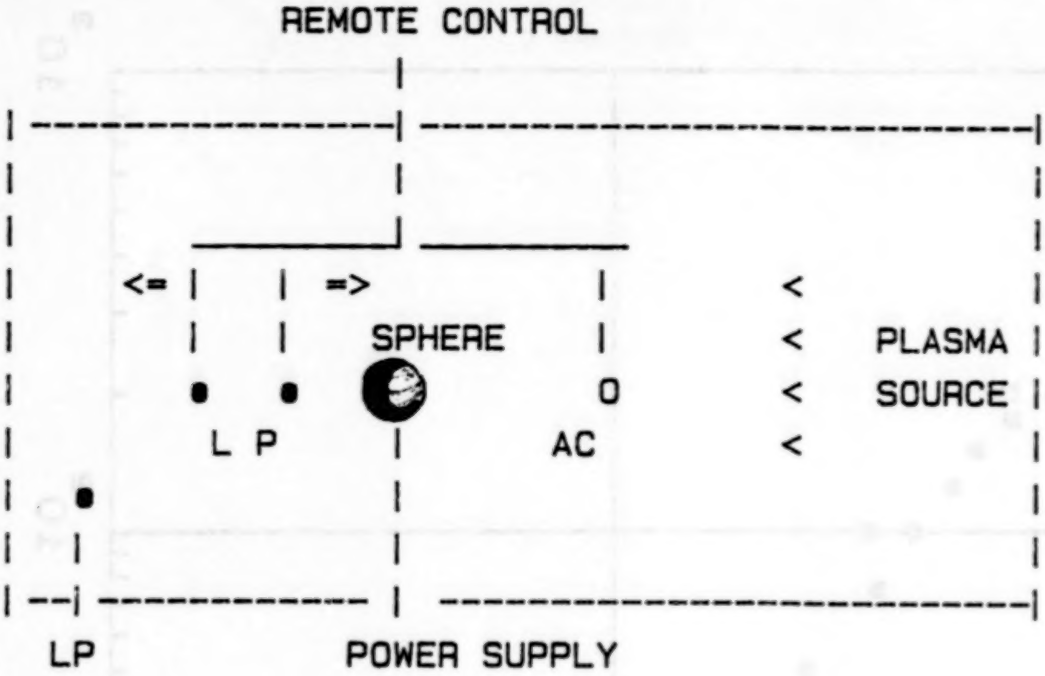

REMOTE CONTROL
<=
=>
SPHERE
PLASMA
SOURCE
L P
AC
O
LP
POWER SUPPLY

FIGURE 1 : FIRST EXPERIMENT SET-UP

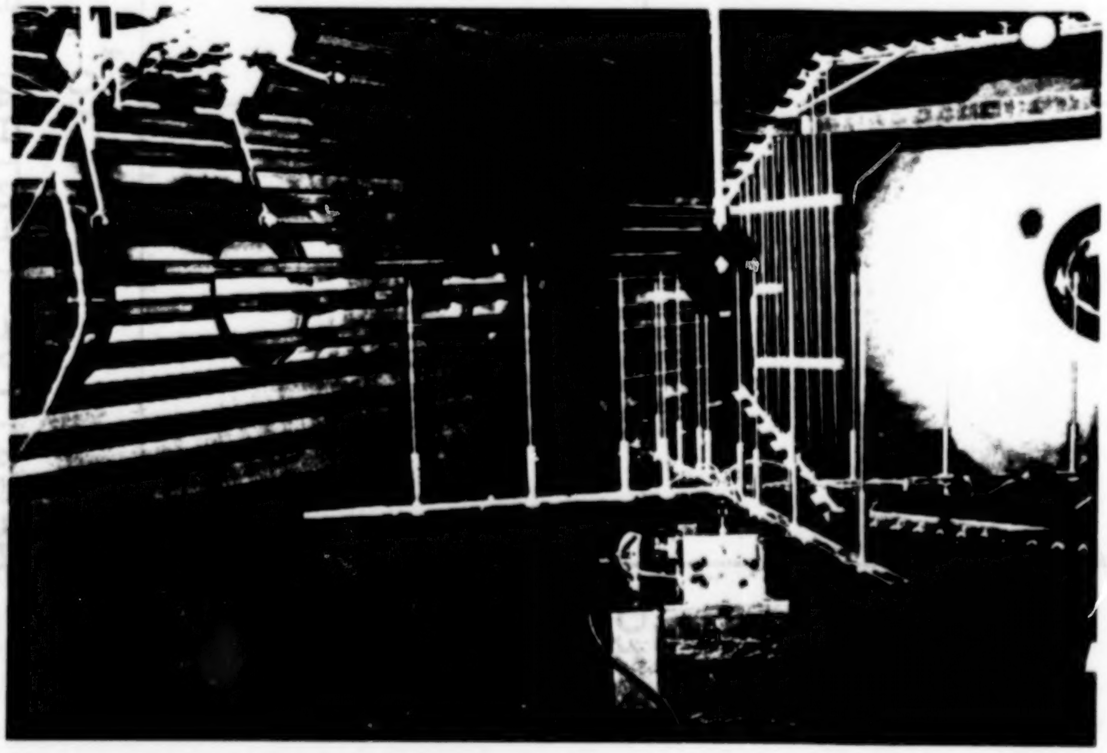


FIGURE 2 : SECOND EXPERIMENT SET-UP

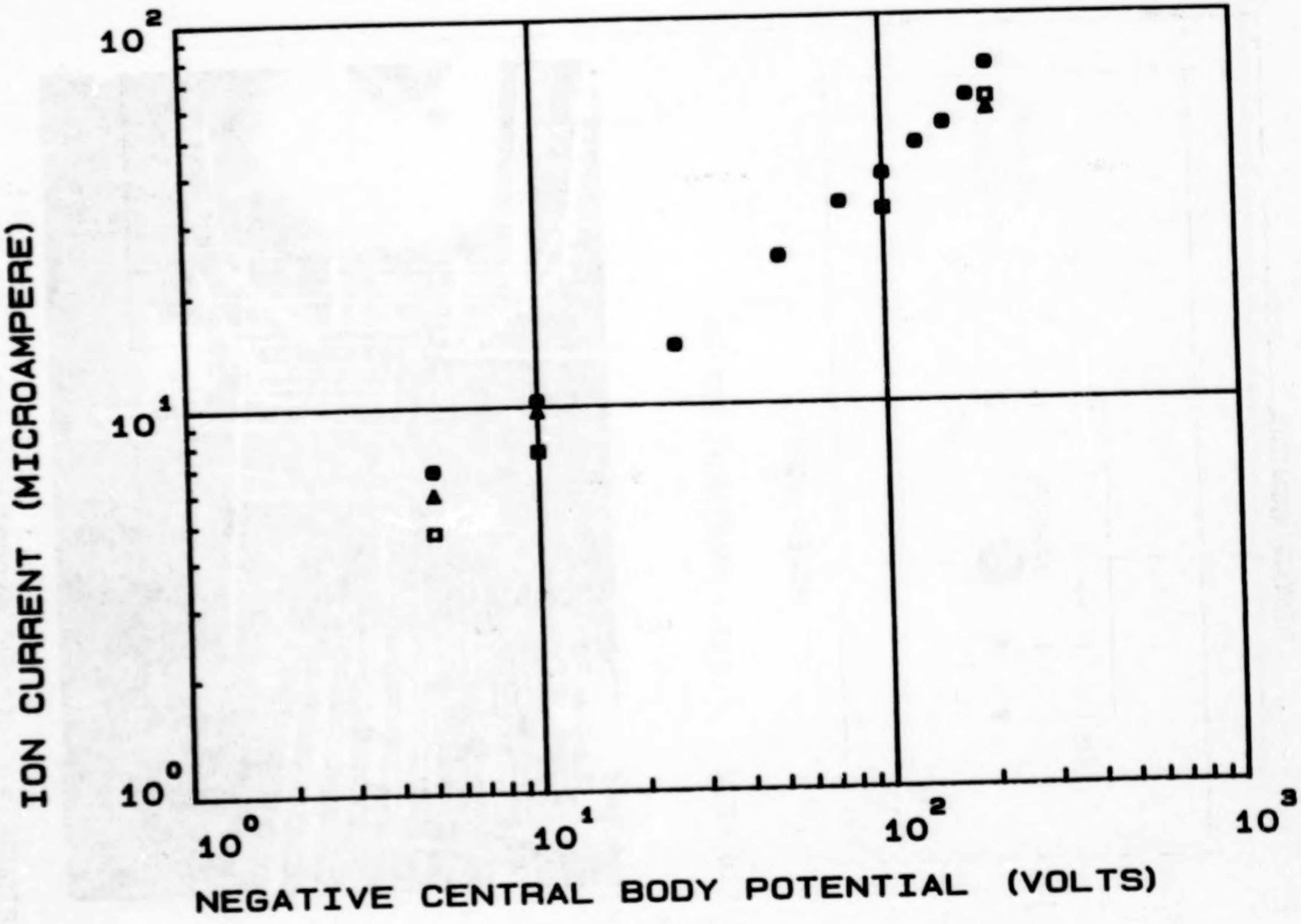
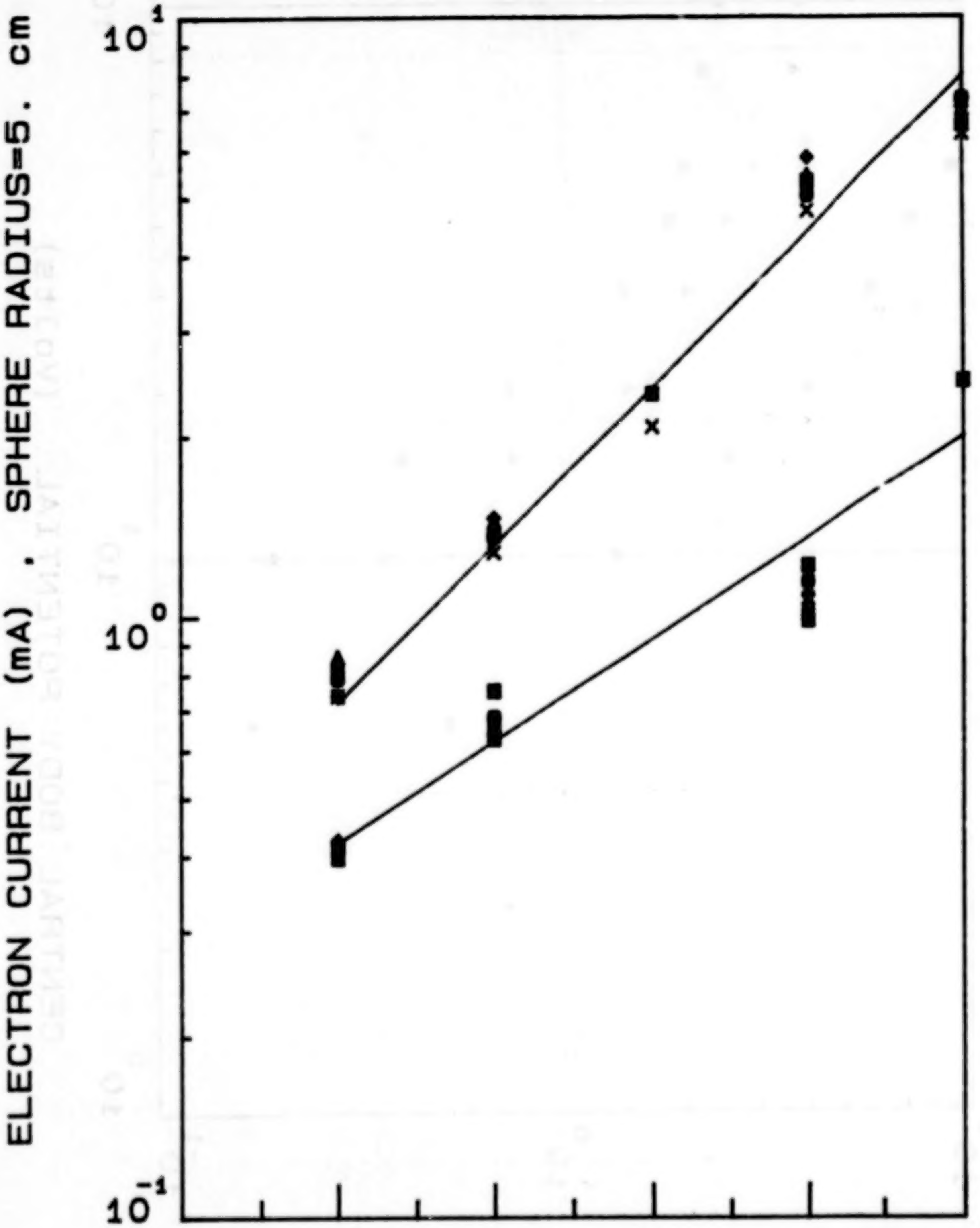

ION CURRENT (MICROAMPERE)
10^2
10^1
10^0
10^0
10^1
10^2
10^3
NEGATIVE CENTRAL BODY POTENTIAL (VOLTS)

FIGURE 3


ELECTRON CURRENT (mA) . SPHERE RADIUS=5. cm
10^1
10^0
10^{-1}
0
10
20
30
40
50
SPHERE POTENTIAL (Volt)

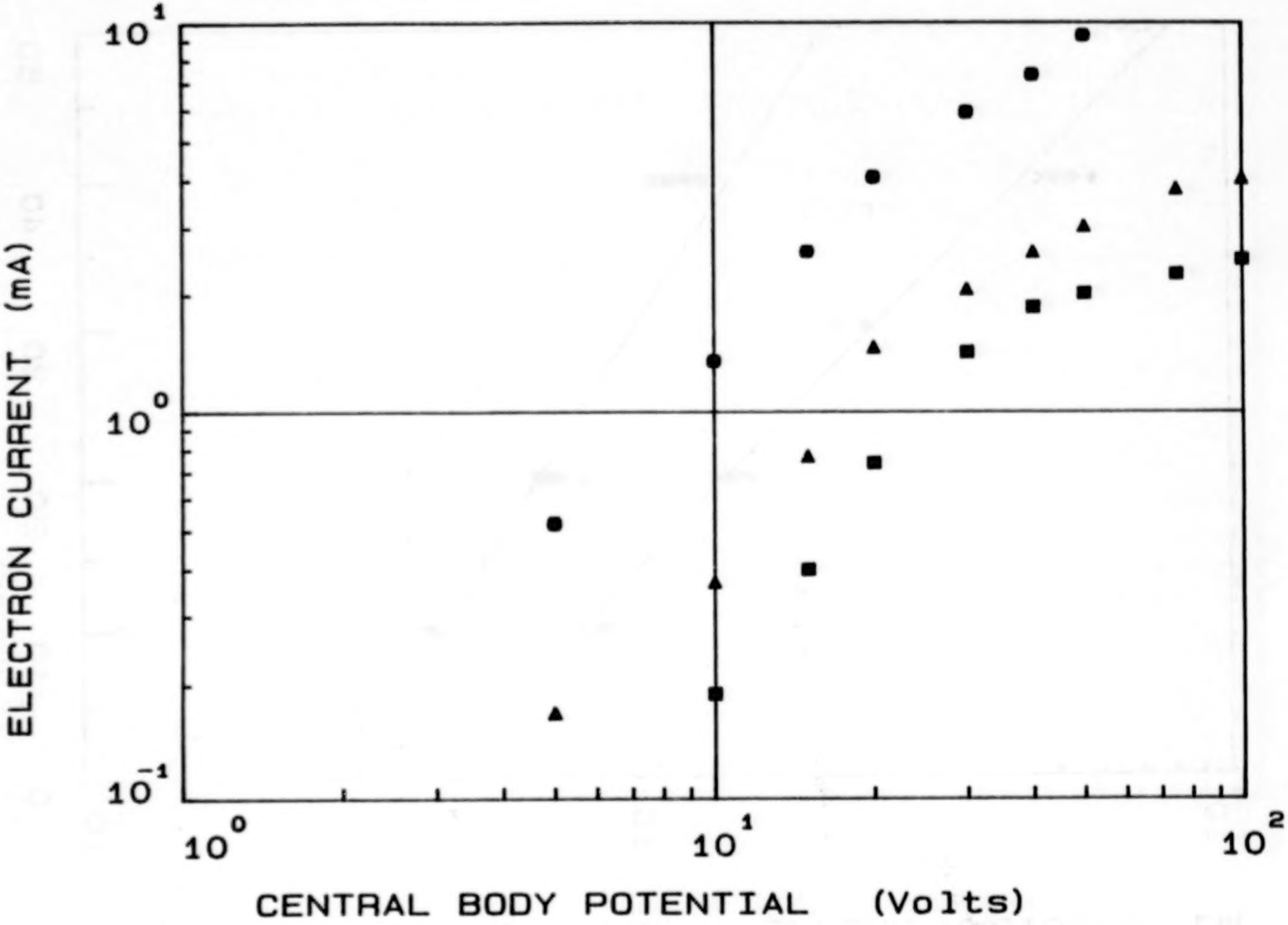

10^1
10^0
10^{-1}
ELECTRON CURRENT (mA)
10^0
10^1
10^2
CENTRAL BODY POTENTIAL (Volts)

FIGURE 5

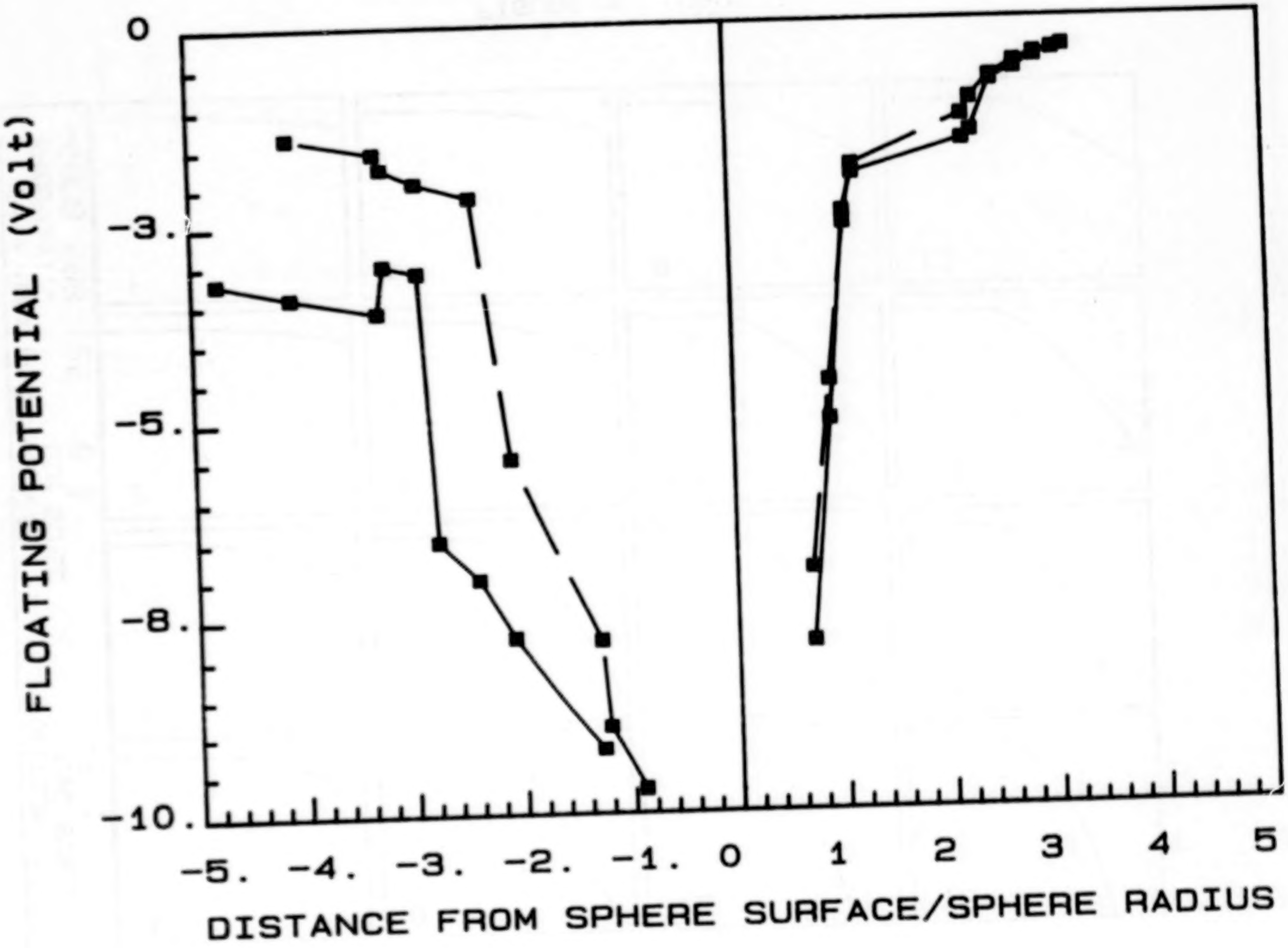

FLOATING POTENTIAL (Volt)
0
-3.
-5.
-8.
-10.
-5.
-4.
-3.
-2.
-1.
0
1
2
3
4
5
DISTANCE FROM SPHERE SURFACE/SPHERE RADIUS

FIGURE 6

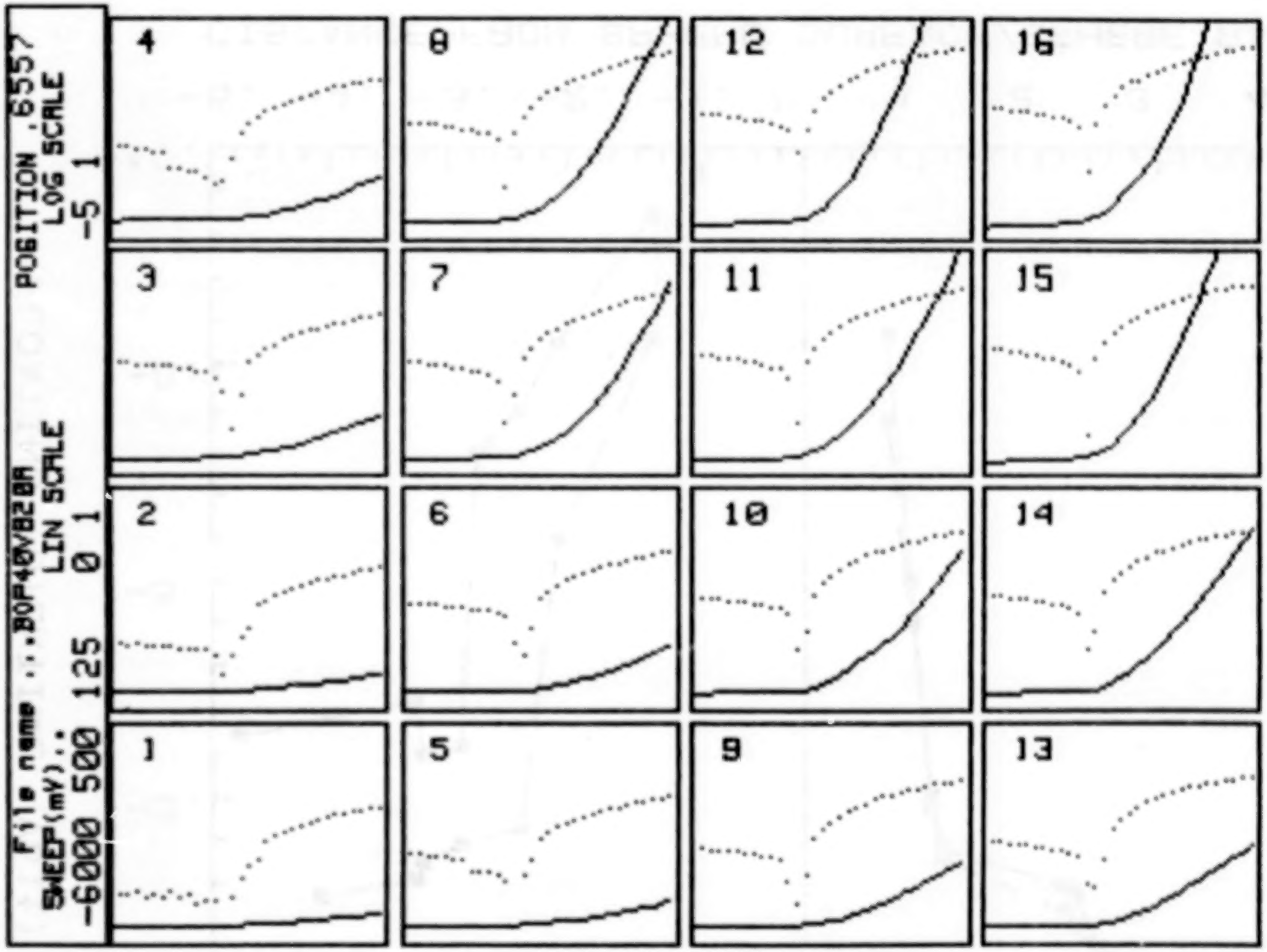

File name ...B0P40VB2BA
SWEEP(mV)..
-6000 500 125 0 1
LIN SCALE
POSITION .6557
LOG SCALE
-5 1
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16

FIGURE 7

	LABORATORY			IONOSPHERE
	RANGE	EXP-1	EXP-2	250 Km
NEUTRAL DENSITY (Toor)	10^{-4} TO 10^{-7}	10^{-5}	10^{-5}	10^{-7}
PLASMA DENSITY (e/cm 3)	10^{4} TO 10^{7}	$3.4\ 10^{5}$	$1.8\ 10^{6}$	$4\ 10^{5}$
ELECTRON TEMPERATURE (K)	500 TO 2000	1340	1860	1700
ION TEMPERATURE (K)	300	300	300	1200
ION MASS	40 (Ar)	40 (Ar)	40 (Ar)	24
ION FLOW (ORBITAL VEL.) (km/s)	5 TO 50	8	8	7.75
STATIC B FIELD (Gauss)	0 TO 2	0.86	0.8 & 1.2	0.35
DEBYE LENGTH (cm)	0.1 TO 1.7	0.47	0.47	0.45
ELECTRON GYRORADIUS (cm)	>0.1	1	2.3 & 1.2	2
ION GYRORADIUS (m)	>10	50	50 & 25	100
PLAMSA FREQUENCY (MHz)	1 TO 30	5.25	10	5.75
ELECTRON GYROFREQUENCY (MHz)	0 TO 5	0 &1.9	22.4 &11.7	1

TABLE 1: PLASMA PARAMETERS IN THE LABORATORY AND IN THE IONOSPHERE

VOLTS	ELECTRON DENSITY X 10^6 (cm^{-3})		
	B= 0 G	B= 0.6 G	B= 1.2 G
-200.	1.23	1.28	1.54
-175.	1.23		
-150.	1.30		
-125.	1.30		
-100.	1.36	1.54	1.70
-75.	1.36		
-50.	1.44		
-25.	1.52		
0.	1.63	1.70	2.02
5.	1.15	1.52	
10.	0.87	1.36	1.80
15.	0.63	1.21	1.64
20.	0.60	1.01	1.24
30.	0.56	0.97	1.18
40.	0.52	0.91	1.18
50.	0.44	0.85	1.12
75.		0.85	1.05
100.		0.78	0.72

Table-2-

Electron density versus test body potential for external magnetic field 0.0, 0.6, and 1.2 Gauss.

N86-28426

NATURAL ELF NOISE EVALUATION FOR TSS EMISSIONS DETECTION ON THE EARTH´S SURFACE

The Electric Field Component Approach

Giorgio Tacconi
University of Genoa, Italy

Abstract: The preliminary estimate of the local noise structure in the proximity of a receiver is essential to establishing the detectability of a given signal in presence of such noise. This memo outlines the possibility of detecting the Electric Field Component of the background noise by means of electric dipoles horizontally placed on the sea bed in shallow waters, in order to find its spectral and statistical characteristics for the definition of the optimal receiving system.

1. Introduction

The detection on the Earth´s surface of possible electromagnetic emissions in the ELF range radiated by the TSS is, in principal, a communication problem. A sufficient amount of energy available at the receiver is, of course, necessary for the operation of any communication system in the presence of background noise. Energy transmission factors are, however, insufficient to evaluate or optimize a receiving system as soon as it includes relatively advanced signal processing techniques. In order to estimate the detectability of a hypothetical signal by a receiver, several pieces of information are needed:

1. Signal characteristics (the transmitter).
2. Boundaries and propagation conditions (the medium).
3. Background noise information in terms of spectral and time/space statistical structure in proximity of the receiver.
4. Receiver characteristics (the receiver).

2. The scenario of the experiment is shown in Figure 1. The space where the propagation of the emission takes place is represented in the main, by a number of layers. In case of detection on the bottom of the sea, the above-mentioned layers are:

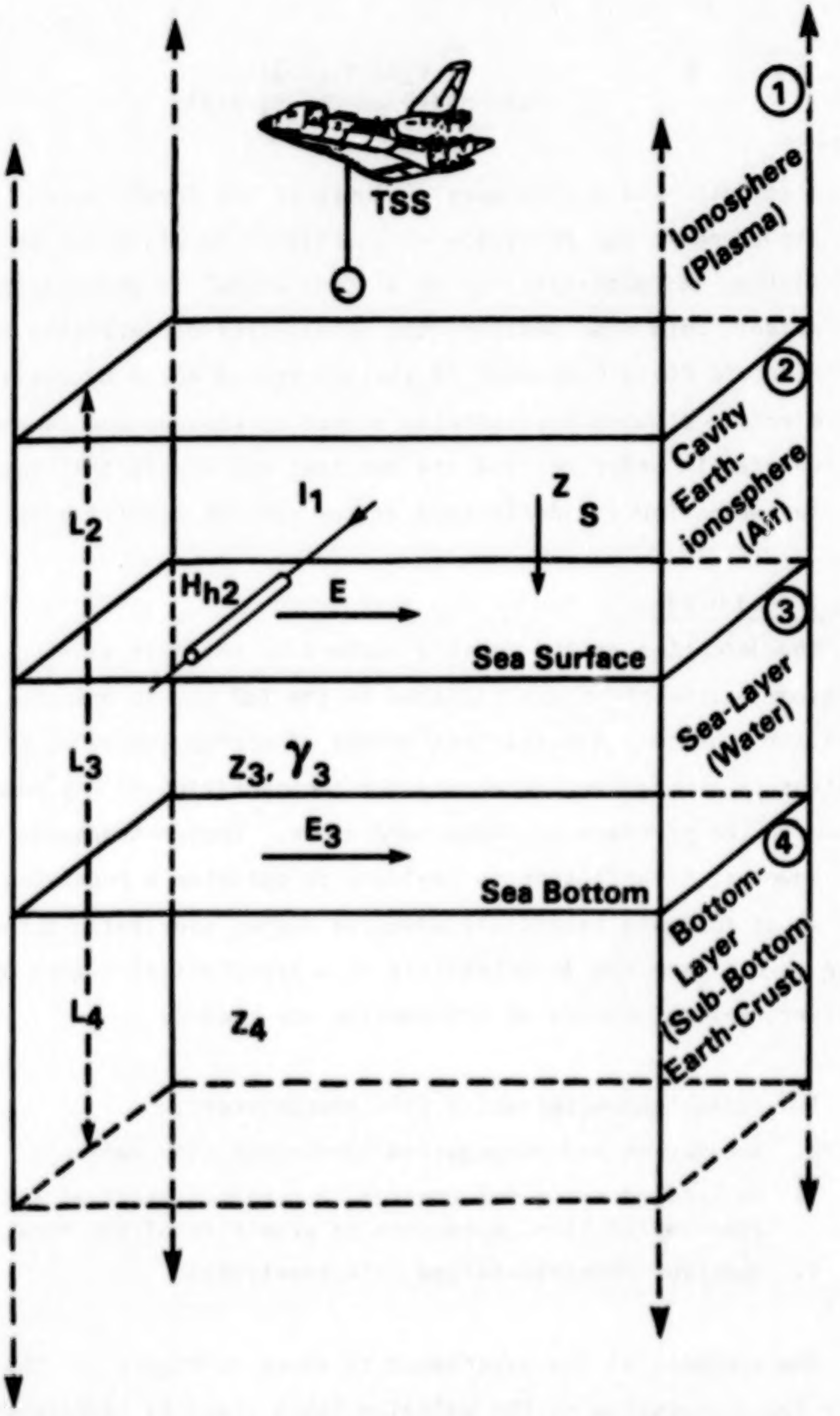

TSS
①
Ionosphere (Plasma)
②
Cavity Earth-ionosphere (Air)
I_1
Z_S
L_2
H_{h2}
E
Sea Surface
③
Sea-Layer (Water)
L_3
Z_3, γ_3
E_3
Sea Bottom
④
Bottom-Layer (Sub-Bottom Earth-Crust)
L_4
Z_4

Figure 1. Propagation Scenario Structure

I. The ionosphere

II. The Earth surface/ionosphere cavity

III. The sea layer

IV. The sub-bottom Earth crust layer

The zone which we are interested in for the present investigation is that related to the II, III, and IV layers of Figure 1.

3. The natural background noise propagates as plane waves from the sea surface to the bottom, where the receiving electric dipole is placed. The water layer is equivalent to a transmission line of length L_3 (Figures 2a and 2b).

The current I in the transmission line (Figure 2b) corresponds to the horizontal component of the magnetic field strength in air, H_{h2}, which is practically independent from the characteristics of the water and the bottom. The load of the transmission line is represented by the bottom impedence Z_4. Assuming the bottom of infinite depth ($L_4 = \infty$), the difference of potential in the water, E_3 is given by:

$$E_3' = H_{h2} \times Z_3 \text{ (for } L_3 = \infty \text{)} \qquad (1)$$

$$E_3'' = E_3' \times \frac{Z_2}{Z_3} \text{ (for } L_3 = \text{finite)} \qquad (1')$$

For a water depth $L_{3f} = L_3$ finite

$$E_3 = H_{h2} \times Z_2 \qquad (2)$$

which gives the ratio:

$$\frac{E_3''}{E_3'} = \frac{Z_2}{Z_3} \qquad (3)$$

and consequently:

$$E_3'' = E_3' \times \frac{Z_2}{Z_3} \qquad (4)$$

$$E_3'' = E_3' \, G \quad (G = Z_2 / Z_3) \qquad (5)$$

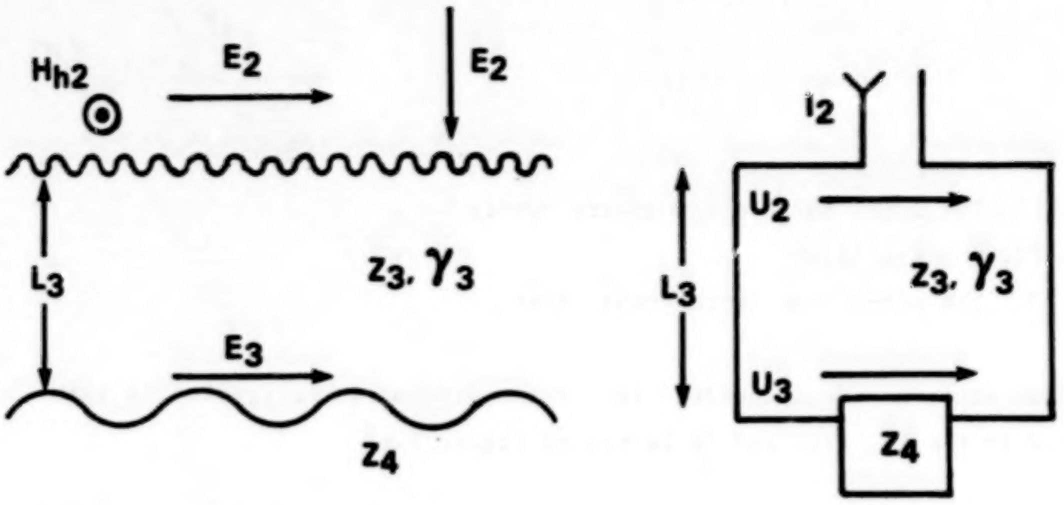


Figure 2a. Figure 2b.

$\gamma_3 = \sqrt{j\sigma_3 \mu_o \omega}$ propagation constant in water

$Z_3 = \frac{j\mu_o \omega}{\gamma_3}$ water impedance

$\gamma_3 = 4$ mhos/m
$\mu_o = 4\pi \times 10^{-7}$ H/m water conductivity
$u = 2\pi f$

Figure 2. Various Quantities Characterizing Propagation in Water

From the theory of transmission lines, we obtain:

$$Z_2 = Z_3 \frac{\tanh \gamma_3 L_3 + \frac{Z_4}{Z_3}}{1 + \frac{Z_4}{Z_3} \tanh \gamma_3 L_3} \qquad (6)$$

This expression is valid for $\sigma \gg \omega\epsilon$ neglecting the displacement currents.

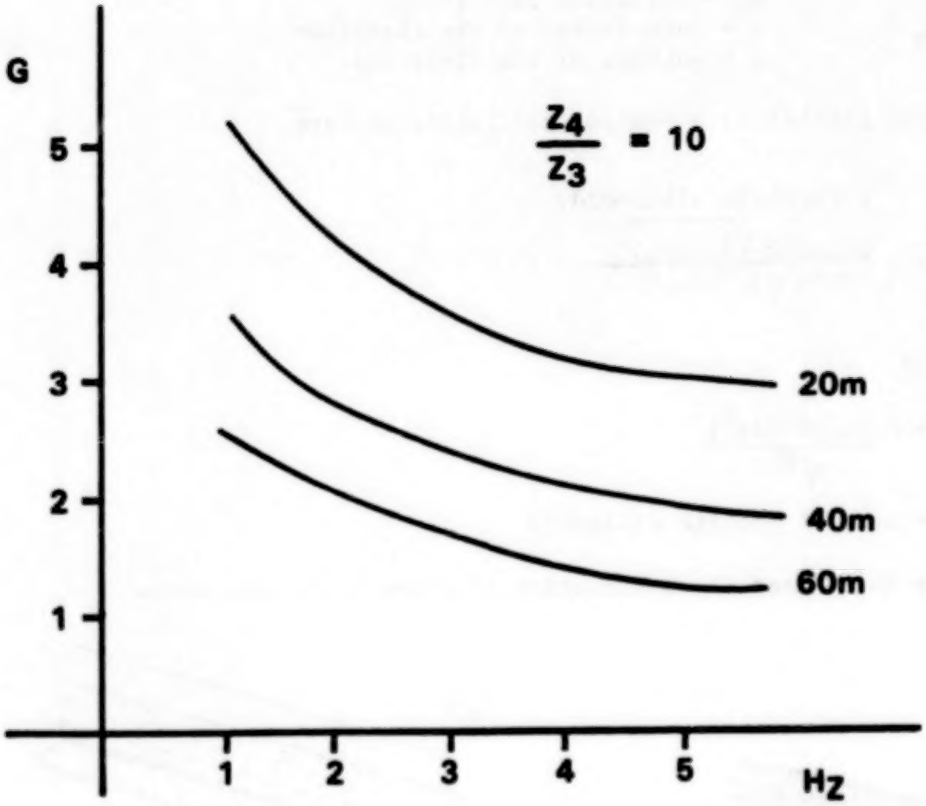
As an example, for $L_3 = 20$ m and assuming $L_4 = \infty$ we have:

$$Z_4 = Z_3 (\sigma_3/\sigma_4)^{1/2} \qquad \begin{array}{l} \sigma_3 = \text{water conductivity} \\ \sigma_4 = \text{bottom conductivity} \end{array} \qquad (7)$$

The observed background noise is increased by the factor $G = Z_2/Z_3$. For a typical value of $\frac{Z_4}{Z_3} = 10$, the factor G is given as a function of frequency for three bottom depths of 20, 40, and 60 m (Figure 3).

4. The electric dipole behavior in sea water is discussed in Reference 1.

The difference in potential between the electrodes of a dipole is:



$$G = \frac{Z_2}{Z_3} \quad \text{For} \quad Z_4 = Z_3 \sqrt{\frac{\sigma_3}{\sigma_4}}$$

Figure 3. The Impedence Ratio G as a Function of Frequency From the Theory of Transmission Lines

$U_{AB} = EL$ L = dipole length

E = electric field component

The impedence of the dipole is:

$$Z_D = R_D \frac{k}{s}$$

R_D = Resistive part of Z_D

k = form factor of the electrode

S = surface of the electrode

for an electrode similar to a prolate ellipsoid, we have:

$$Z_D = R_W + 2R_z \text{ (prolate ellipsoid)}$$

$$Z_D = R_W + 2\,\frac{\operatorname{arctanh}\sqrt{1-(b/a)^2}}{2\pi\sigma a\sqrt{1-(b/a)^2}}$$

and for $\frac{a}{b} = 50$*

$$Z_D = R_W + 2\,\frac{(0.08(\Omega/m^2)}{\sqrt{S}}$$

*"a" and "b" = axis of prolate ellipsoid

Figure 4 shows the phases of construction of a low instrinsic noise electrode.

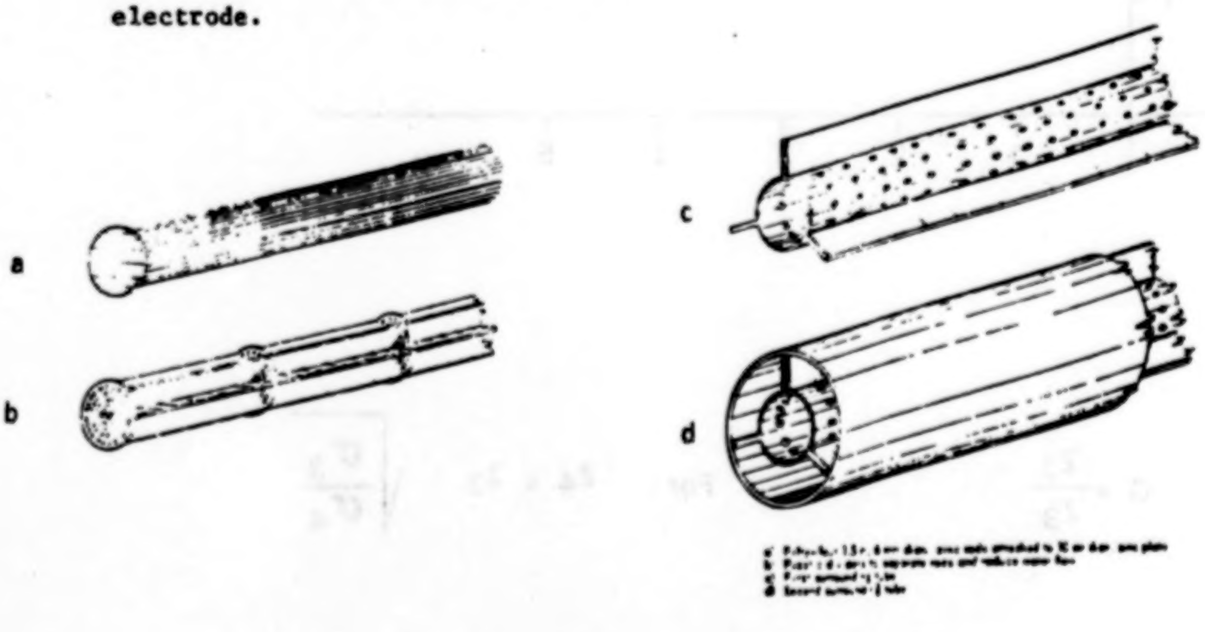


Figure 4. Construction of a Low Noise Electrode

Figure 5 shows an experimental dipole assembly 7 m long. Two such dipoles were horizontally placed on the sea bottom parallel to each other and separated by 1 km. Performances of such systems can be strongly improved with new design and construction.

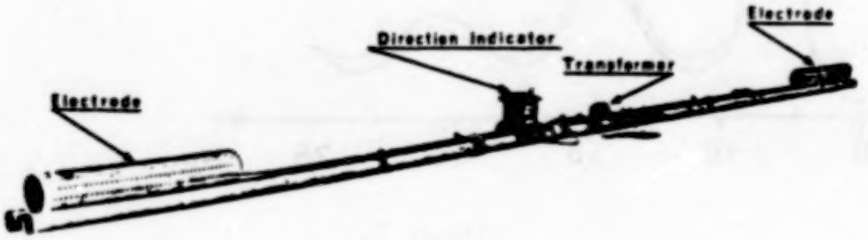


Figure 5. Experimental Dipole Assembly

Figure 6 shows the power spectra of the two signals simultaneously recorded. Here we observe the space correlation effect which reduces the far off noise (Shuman modes).

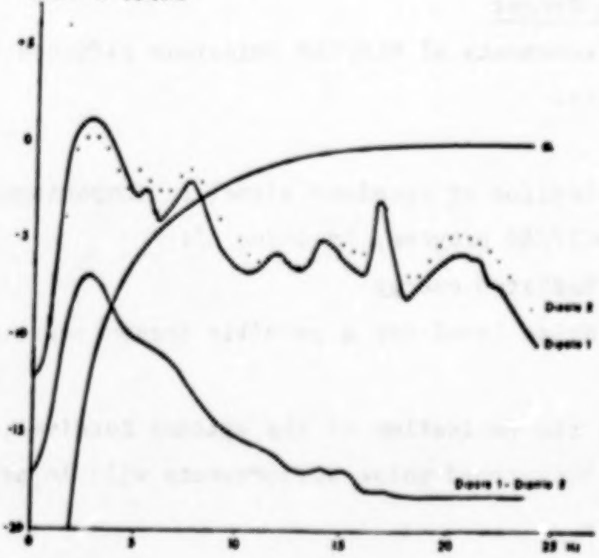


Figure 6. Power Spectra of Natural Background Noise Measured by Two Dipoles 1 km Apart and of the Difference Signal. (The power spectra are multiplied by the factor a)

Figure 7 shows theoretical and measured ELF background noise (J. Galejs and Balzer & Wagner). The first three Shuman modes are evident.

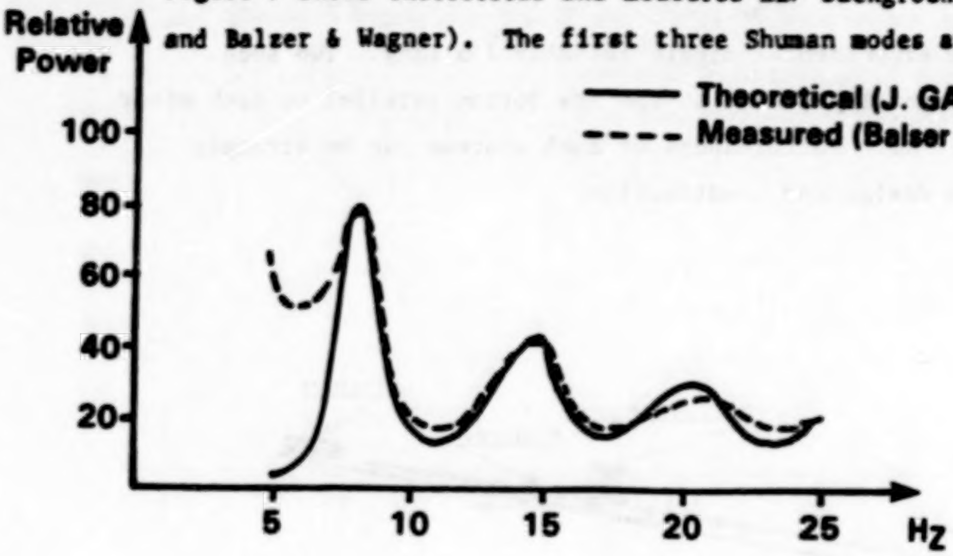


Figure 7.

6. Concluding Considerations

Simultaneous recording of horizontal electric E_n and horizontal magnetic H_n field components should give a highly reliable validation of the theoretical estimate of the electromagnetic field distribution on the Earth's surface.

a. The Target

Measurements of VLF/ELF emissions radiated by the TSS at Earth's surface.

o Evaluation of received signal in comparison with theoretical estimate of MIT/SAO program, in terms of:

- Radiated energy
- Noise level for a possible transmission channel.

oo For the derivation of the optimal receiver, preliminary natural and man-made background noise measurements will be performed at the selected site.

b. The Site

The choice of the most favorable site depends on the results of the MIT/SAO program. Anyway, a possible selection of sites is as follows:

- Tynerian Sea (Tino) in case of guided propagation
- Central Med. (Lampedusa) - compromise conditions
- Canary Islands (Spain) - closest point of approach - hot spot

Logistic problems will be solved by the Italian Navy - CNR - and tentatively, by the Spanish Institute Astrofineo de Canarias (Tenerife).

c. The Instrumentation

Special coil sensors are supplied by NUSC (M. E. Soderberg) - presently in calibration. Cesium magnetometers (total field) will also be used.

Recording equipment (multichannel FM tape recorder battery operated) and general instrumentation with additional electronics will be supplied by the University of Genoa (DIBE), the Italian Navy, CNR, and Saclantceu (la Spezia).

d. Received Data and Analysis

From the preliminary investigation on local noise, which is expected to be non Gaussian, and its characterization on Type A or B (Middleton), the structure of optimal receiver will be derived, i.e, LOTR (Locally Optimum Threshold Receiver). This process and subsequent spectral analysis and signal processing will be done at the University of Genoa (DIBE).

To establish a common methodology for obtaining comparable results, we are in contact with other groups interested in detecting TSS emissions:

- Rice University, Professor Gordon
- Stanford University, Prof. Hellinell

Analytical cooperation will be given by various Italian groups:

- Univ. Florence - Prof. Buscagliosi:
  Prof. Pellegrini
- Marconi Italiana - Prof. Martini
- CNR-IAN - Prof. Volta.

7. References

1. G. Tacconi, "Fundamentals of ELF Communications and Detection," AGARD Lecture Series No. 88, Oslo-Denhelder-Rome, Oct. 1977.
2. G. Tacconi, "On the Evaluation of Man Made Electromagnetic Noise Interfering with Communications in the ELF Range," AGARD EPP Meeting, Paris, Oct. 1974.

N86-28427

SPONTANEOUS RADIATION EMITTED BY MOVING TETHERED SYSTEMS

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Istituto Fisica Spazio Interplanetario, CNR Italy

I will first outline some concepts related to radiation emitted by a large conductor moving through a magnetoplasma and refer them to the case of long tethers. Next, I will show some recent results of a theoretical calculation of Alfven wings, their structure and the power associated with them. I anticipate that these results are different from those foreseen, on the basis of qualitative reasoning by Drell et al. (1965) and that we have understood the reason for this difference.

In Figure 1, I have sketched how the problem of radiation from TSS or, more generally, for any large conductor moving through a magnetoplasma, should be approached. The approach is that of the theory of antennas in plasmas. What I have written is the equation for the space-time Fourier transform of the electric field radiated from the moving conductor with, on the right hand side, the transform of the current on the conductor.

We refer to the case of no pulsation of the current; in other words, we look at the electromagnetic fields emitted just because of the motion. The function $\delta(\omega - u_x V)$ on the right hand side is the effect of such motion, with velocity V in the x direction, and tells us a very important point: only plasma modes whose dispersion relation satisfy the Cerenkov condition

$$\omega = K_x V$$

will be radiated by the moving conductor. In a paper by Belcastro et al. (1982), we have analyzed this relation in the context of cold plasma theory with the conclusions which I have summarized in the viewgraph: 1) in the domain of hydromagnetic frequencies, only Alfven waves and not magnetosonic modes can be radiated. In addition, these Alfven waves have propagation vectors almost perpendicular to the magnetic field. In terms of the angle θ between $\underline{K}$ and $\underline{B}$, the solutions to the Cerenkov condition are

$$\theta_1 = \text{arctangent}\ \frac{V_A}{V}$$

$$\theta_2 = \pi - \theta_1$$

2) going to higher than hydromagnetic frequencies, it is found that the resonance condition is satisfied only for frequencies close to the three plasma resonance frequencies $W_{1\infty}$, $W_{2\infty}$, and $W_{3\infty}$ which are the frequencies where the index of refraction goes to infinity. For the case of parallel propagation, these three frequencies correspond to the ion cyclotron frequency, the electron cyclotron frequency and the electron plasma frequency, respectively. They do, however, vary with the angle of propagation, and in Figure 2 I have shown the corresponding variations. For example, we see that $W_{2\infty}$, going from parallel to perpendicular propagation, goes from the electron cyclotron frequency to the lower hybrid frequency and therefore covers essentially all the whistler range. In any case, this shows the range of possible frequencies radiated by a given moving conductor in a plasma as a consequence of the Cerenkov radiation condition.

There are actually other limitations to the frequencies emitted which have to do with the dimensions of the conductor transverse to the direction of motion. This is shown in Figure 3. The potential difference across the conductor is applied for a time

$$T \sim \frac{D}{V}$$

equal to the time the conductor takes to cross its dimension D perpendicular to its direction of motion. The inverse of this time

$$f^* \sim \frac{1}{T}$$

is clearly an upper limit to the frequencies of the electromagnetic perturbations emitted by the conductor (in the sense that there will be no significant power emitted for frequencies $f > f^*$). Thus, we see that, in order to have a pure hydromagnetic perturbation associated with the conductor, we need

$$f^* < f_{ci}$$

and, hence, very large conductor dimensions

$$D \geq 40 \text{ meters}$$

This is not the case for TSS and, indeed, the electromagnetic perturbation associated with TSS will be something more complicated than pure Alfven waves. For TSS, if we take as a reference the satellite dimensions ($D = 1.2\text{m}$) we get

$$f^* \sim 6.6 \text{ kHz}$$

which falls in the whistler range.

After precising these concepts related to the frequencies emitted by TSS, let me show results of a formal calculation of the Alfven wave radiation emitted by a large conductor (Dobrowolny and Veltri, 1985).

Figure 4 reports first of all our results for the power radiated in Alfven waves.

As applied to TSS, this gives, for a tether length $L = 100$ km and a current $I = 1$ ampere, only a few watts of power. The point that I want to bring, however, is that this calculated power is different from that estimated early by Drell et al.(1965) which I have written in the next line of the viewgraph. What we find is precisely a factor $(V/V_A)^2$ smaller which is a considerable reduction. I think we understand now the reason of the difference and that our result is right and I would like to explain that.

In the remaining part of the figure I am showing the way Drell et al. did their estimate and the conceptual mistake which is hidden there. Drell et al. estimated power from

$$P \sim \frac{\delta B^2}{8\pi} \quad V_A S$$

Here it is supposed that an alfvenic perturbation δB is propagating with velocity V_A along magnetic field lines. The formula is all right provided that one uses in there the correct estimate for δB. To arrive at their result, Drell et al. used

$$\delta B \sim \frac{I}{D}$$

which, as you see, is the field associated with a constant current (in the magnetic field direction). Now, there is such a field and there is power associated with it, but that happens just because the current is moving; and it is moving not with the velocity of V_A but the conductor's velocity V and not in the magnetic field direction, but in the direction of motion. If we use this δB in the estimated power, we have to multiply the corresponding energy not by $V_A S$ but by

$$\underline{V} \cdot \underline{S} = V \frac{V}{V_A} S$$

so that we end up with a factor $\left(\frac{V}{V_A}\right)^2$ of reduction with respect to Drell et al.

On the other hand, we can use the above formula for estimating power provided we use there not the δB of the constant current but the δB_A of the alfvenic perturbation. Now it can be seen very easily that

$$\delta B_A \sim \frac{K_{\parallel}}{K_{\perp}} \delta B \sim \frac{v}{V_A} \delta B$$

where the last inequality is due to the Cerenkov condition that was discussed before. If we use this expression we end up with our formal result.

Thus the power spontaneously radiated in Alfven waves is of the order of 1 watt. But, remember that that is not the only power emitted by the tether. There is power in higher frequencies as well. Besides, nobody has looked yet at warm plasma phenomena and, for example, on how much power is emitted in Bernstein modes from the tether.

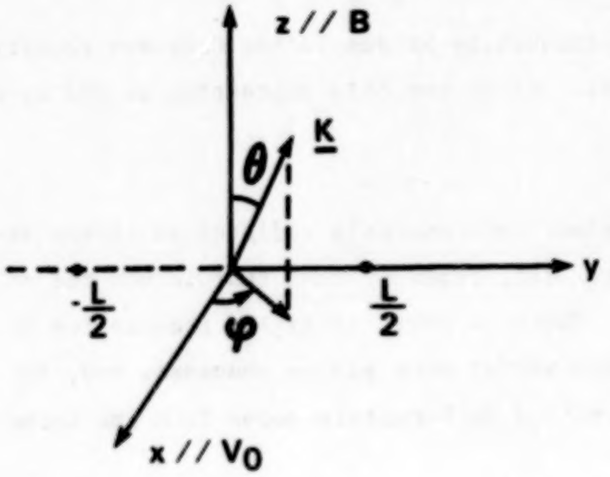
References

1. S. D. Drell, H. M. Foley, M. A. Ruderman, J. Geophys. Res 70, 3131, 1965.
2. V. Belcestro, P. Veltri, M. Dobrowolny, Il Nuovo Cincento C 5, 537, 1982.
3. M. Dobrowolny, P. Veltri, to be published in Nuovo Cincento, 1985.

FIGURE 1

Radiation From The Moving Tether

— Current Source: $J_0 = J_0(x - V_0 t, y, z)$



— Radiated Electric Field:

$$\Lambda_{ij}(\underline{K},\omega)\, E_j(\underline{K},\omega) = -\frac{i}{\omega}\,\delta(\omega - K_x V_0)\, J_{0i}(\underline{K})$$

$$\Lambda_{ij} = \eta^2 (x_i x_j - \delta_{ij}) - \epsilon_{ij}$$

$\det \Lambda_{ij} = 0$ ⟶ **Dispersion Relation**

— Resonance Condition:

$$\omega = k_x V_0 \quad \text{or} \quad \eta(\omega, \theta, \varphi) = \frac{c}{V_0 \sin\theta \cos\varphi}$$

— Radiated Modes:

Alfven Waves for $\omega < \Omega_{ci}$ $\left(\theta = \arctan \frac{V_A}{V}\right)$

Quasi-Longitudinal Waves Near Resonant Frequencies

$(\Omega_{ci}, \Omega_{ce}, \omega_{pe})$

FIGURE 2

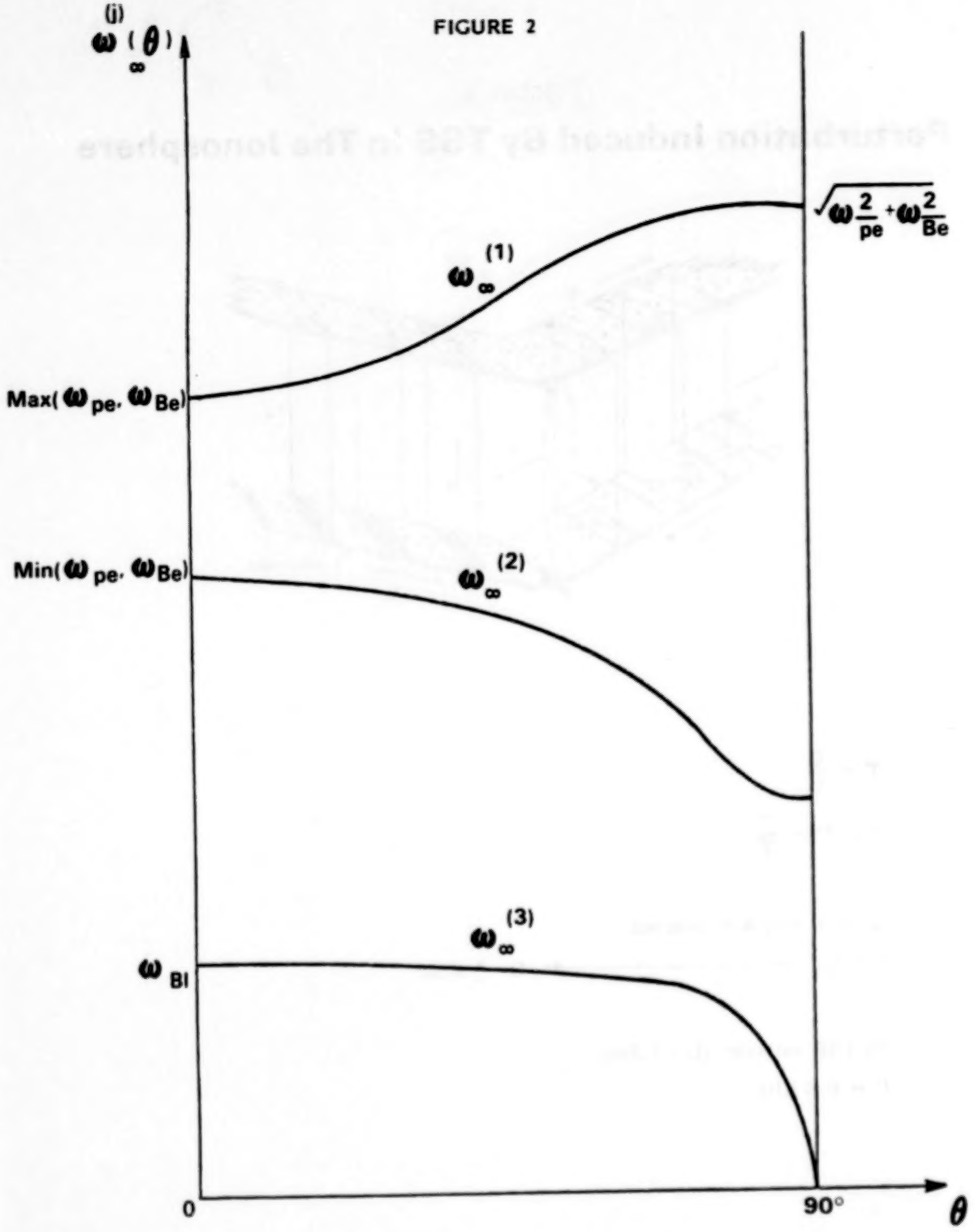
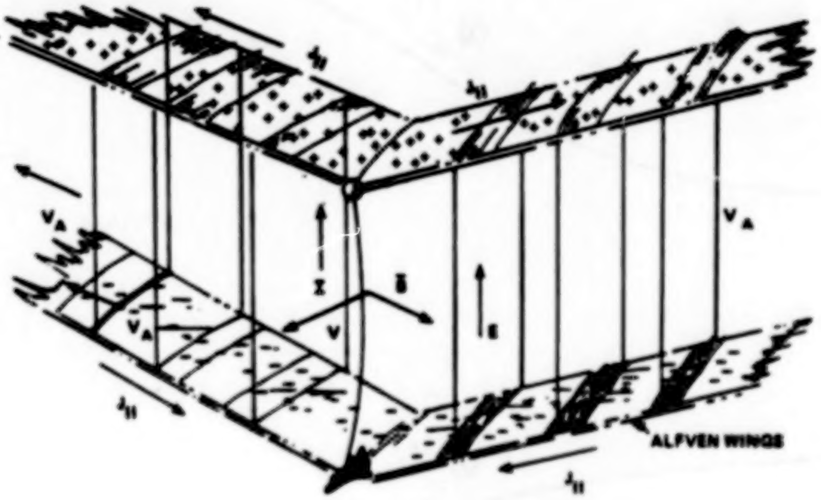

$\omega_\infty^{(j)}(\theta)$
$\sqrt{\omega_{pe}^2+\omega_{Be}^2}$
$\omega_\infty^{(1)}$
Max(ω_{pe}, ω_{Be})
Min(ω_{pe}, ω_{Be})
$\omega_\infty^{(2)}$
$\omega_\infty^{(3)}$
ω_{Bi}
0
90°
θ

FIGURE 3

Perturbation Induced By TSS In The Ionosphere


$j_{\parallel}$
$j_{\parallel}$
V_A
V_A
X
$\bar{B}$
V_A
V
I_E
$j_{\parallel}$
ALFVEN WINGS
$j_{\parallel}$

$$\tau \sim \frac{D}{V}$$

$$f \lesssim f^* \sim \frac{1}{\tau}$$

To have only AW radiated:

$$f^* < f_{ci} \xrightarrow{\qquad\qquad} D \gtrsim 40\text{m}$$

for TSS satellite (D = 1.2m):

$$f^* \sim 6.6 \text{ KHz}$$

FIGURE 4

Power Radiated By TSS In Alfven Waves

Belcestro, Dobrowolny, Veltri, 1982

Dobrowolny, Veltri, 1985

$$P_{AW} \simeq \frac{V_A}{C^2} \frac{L}{D} \left(\frac{V_0}{V_A}\right)^2 I^2 \qquad = \left(\frac{V_0}{V_A}\right)^2 P_{DFR}$$

from early estimates of Drell, Foley, Ruderman:

$$P_{DFR} = \frac{V_A}{C^2} \frac{L}{D} I^2$$

$$P_{DFR} \sim \frac{\delta B^2}{8\pi} V_A S$$

$$\delta B \sim \frac{I}{D}$$ (field associated with dc current)

this field is moving with volocity V (not V_A) and not in the magnetic field direction

— Alfvenic field $$\delta B_A \sim \frac{K_{\parallel}}{K_{\perp}} \delta B \sim \frac{V}{V_A} \delta B$$

---

for $L \sim 100$ km $\qquad I = 1$ ampere

$$\longrightarrow \quad P_{AW} \sim 1 \text{ watt}$$

N86-28428

TETHERED SATELLITE SYSTEM (TSS)

CORE EQUIPMENT

CARLO BONIFAZI

CNR/PSN Principal Investigator

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1.0 SCOPE

1.1 Introduction

The Tethered Satellite System (TSS) project is jontly supported and funded by the U.S. and Italian governments. It will consist on an Italian provided scientific Satellite (500 kg) orbiting in the ionosphere connected to the Space Shuttle (Orbiter). To date three are the TSS missions foreseen (References 1 and 2). The first mission, to date scheduled at the end of 1988, will use an electrically conductive Tether of 20 km deployed upward from the Orbiter flying at 300 km altitude. This mission will allow investigation of the TSS electrodynamic interaction with the ionosphere due to the high voltage induced across the two terminators of the system during its motion throughout the geomagnetic field. The second mission, to be scheduled, will use a dielectric Tether of 100 km deployed downward from the Orbiter flying at 230 km altitude. Tethered-vehicle access to altitude as low as 120-150 km from the Orbiter would permit direct long-term observation of phenomena in the lower thermosphere and determination of its composition, observation of crustal geomagnetic phenomena, and measurement of other dynamical physical processes which affect the atmosphere, and ionosphere. Finally, the third mission, to be scheduled, would use the same configuration of the first electrodynamic mission with the complete Core Equipment (Reference 3). In particular study of power generation by tetherd systems would be possible by operating the Core Equipment i the inverted current mode. This mode of operation would allow ion current collection upon the TSS Satellite by controlling its potential with respect to the ambient ionospheric plasma.

This report is intended to describe the main requirements of the Core Equipment configuration to date foreseen for the first TSS electrodynamic mission. In particular, besides the Core Equipment purposes, its hardware and operational sub-modes of operation are described.

The TSS Core Equipment is jontly supported and funded by U.S. and Italian governments in a manner similar to the overall TSS project. The CNR/PSN team responsible for the Italian- provided Core Equipment consists of Dr. Carlo Bonifazi, as Principal Investigator; Dr. G. Manarini, as Program manager; and Dr. J. Sabbagh, as Project manager.

1.2 Core Equipment Definition

The Core Equipment of the Tether Satellite System (TSS) will consist of items of equipment and supporting software which are necessary for the general scientific and technological utilization of the TSS facility. The Core Equipment functional items identified in this document are:

a. Tether Current-Voltage Control system (TCVC) for the conducting Tether;

b. Three-Axis Accelerometer-Gyro system (TAG) to support Tethered Satellite-born studies of TSS Satellite dynamics as first step toward use of the TSS for study of crustal-induced magnetic and geodynamic processes.

These items are necessary to support the first TSS mission. However it is recognized that additional items of Core Equipment may be required on subsequent missions as more sophisticated use is made of the TSS facility.

1.3 Core Equipment purpose

The TSS Core Equipment will provide general support essential to a wide variety of scientific and technological investigations carried out either on the Tethered Satellite or the Tether Deployer, which is mounted on the Orbiter. Specifically, for the electrodynamic mission the TCVC system will allow control of the TSS-S electrical potential by varying the current that flows between the Satellite and the Orbiter through the Tether as a result of the emf generated by motion of the TSS through the geomagnetic field.

This function is fundamental to the operation of the electrodynamic Tether and is essential for pratically all the scientific investigations of space plasma physics and electrodynamic phenomena which utilize the TSS.

Three-Axis Accelerometer-Gyro system (TAG)will provide accurate assessment of dynamic perturbations to the motion of the TSS Satellite.

This information is required to determine the suitability of the TSS Satellite as a platfoprm for a variety of investigations of crustal-induced magnetic and gravitational effects.

2.0 HARDWARE DESCRIPTION

2.1 Tether Current-Voltage Control system (TCVC)

The TCVC system will consist of the following items:

2.1.1 Satellite Core Equipment

Satellite Main Switch: a parallel redundant, slow acting switch capable of electrically isolating the Tether from the Satellite conductive skin. This is a cold type switch.

Core Tether Current Monitor: a slow sample rate monitor of the current flowing down the Tether. This instrument is connected between the Satellite conductive skin and the Satellite Main Switch.

2.1.2 Deployer Core Equipment

Deployer Master Switch: a high voltage, hot type, parallel redundant switch which can provide electrical isolation of the Tether from the Deployer/MPESS mounted science. In particular, it can connected the Tether to the Core Electron Generator (CEG) via the Tether Current Sensor.

Tether Current Sensor: a one Ohm shunt resistor in series with the Tether between the Deployer Master Switch and CEG. It is anticipated that this shunt resistor will be part of the SETS current and voltage measuring devices (TCVM) which allow high frequency sampling of Tether current and voltage.

Core Electron Generator (CEG): an electron source capable of providing up to 500 mA of electron beam current at a cathode-to-anode voltage of 3000 V (1000 V as design goal).It consists of two identical CEG heads, each one able of providing the maximum current, which will assure the CEG redundancy. In addition, each CEG head has the capability to be disconnected from the Deployer end of the Tether in case of failure by a switch which is identical to those forming up the Deployer Master Switch.

Gas Pressure Monitor: a vacuum gauge mounted in the vicinity of the CEG to detect pressure surges to levels at which damage to CEG might occur.

Core Tether Voltage Monitor: a slow sampling rate monitor of the voltage between the Deployer end of the Tether and the Orbiter electrical ground.

Three-Axis Aspect Magnetometer: a low sensitivity magnetometer used to determine the magnetic field of the Orbiter Payload Bay. It will be used to determine the pitch angle and azimuth of the CEG and the SETS Fast Pulse Electron Gun (FPEG) beams during the mission. It is anticipated that the Aspect Magnetometer will be provided by NASA.

2.2 Three-Axis Accelerometer-Gyro system (TAG)

2.2.1 Satellite Core Equipment

The TAG will consist of a three-axis accelerometer and a three-axis gyro. It is anticipated that the accelerometer will be mounted in the Payload Module of the TSS Satellite and the Gyro package of the Satellite Attitude Measurement and Control Subsystem (AMCS) will serve as a Core Equipment Gyro. The accelerometer should be mounted as close as possible to the Satellite axis of rotation to minimize the acceleration induced by Satellite spin.

3.0 CONFIGURATION

The Core Equipment configuration, defined in the present chapter, is shown in Figure 3.0-1. Depending on its location the Core Equipment will be identified as:

- SCORE, TSS Satellite mounted Core Equipment
- DCORE, TSS-D/Pallet or MPESS mounted Core Equipment

Depending on the performed functions, the Core Equipment will be divided into:

- Tether Current-Voltage Control system (TCVC), which will allow investigation of the TSS-S electrical potential with respect to the ambient plasma by varying the current flowing through the Tether. The TCVC system is the electrodynamic part of the Core Equipment and will consist of DCORE and SCORE items.

- Three-Axis Accelerometer-Gyro system (TAG), which will provide accurate assessment of the dynamic perturbations to the TSS-S motion. This information is required to determine the TSS-S suitability as a platform for investigations of crustal induced magnetic and gravitational effects. The TAG is the dynamic part of the Core Equipment and will consist of SCORE three-axis accelerometer and the TSS-S AMCS gyro package. The Core Equipment will consist of the units and sub-assemblies detailed in the following Table along with their location and functional assignments:

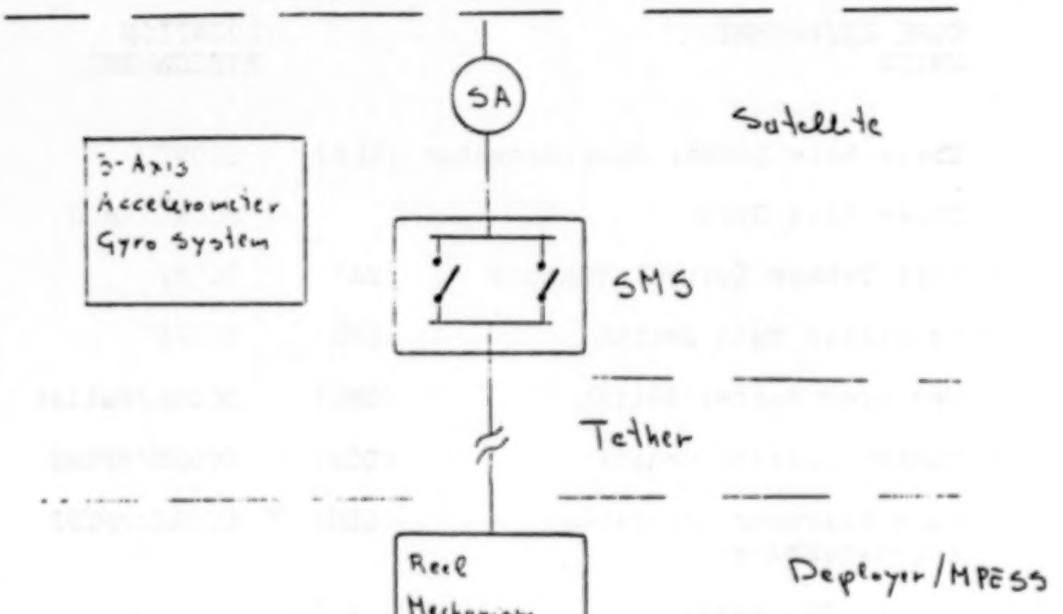
CORE EQUIPMENT UNITS		LOCATION ASSIGNMENT	FUNCTIONAL ASSIGNMENT
- Three-Axis Linear Accelerometer	(SLA)	SCORE	TAG
- Three-Axis Gyro		SCORE/AMCS	TAG
- Core Tether Current Monitor	(SA)	SCORE	TCVC
- Satellite Main Switch	(SMS)	SCORE	TCVC
- Deployer Master Switch	(DMS)	DCORE/Pallet	TCVC(*)
- Tether Current Sensor	(TCS)	DCORE/MPESS	TCVC(**)
- Core Electron Generator: sub-assemblies	(CEG)	DCORE/MPESS	TCVC
a. two CEG Heads	(CEGH1 & 2)		
b. two Filament and Pulsing Power Supplies for CEGH1 & 2	(FPPS1 & 2)		
c. CEG Heads Switching device	(CEGHS)		
- Power Distribution and Electronic Control Unit	(PDECU)	DCORE/MPESS	TCVC
- Gas Pressure Monitor	(DVG)	DCORE/MPESS	TCVC
- Core Tether Voltage Monitor	(DV)	DCORE/MPESS	TCVC
- Three-Axis Aspect Magnetometer		DCORE/MPESS	TCVC(**)

- Table 3.0-1 -

(*) The Deployer Master switch shall be supplied by Aeritalia. Its power, commands, and monitors shall be provided by NASA-MMA. Its operations shall be synchronized with the TCVC SCORE and DCORE operations.

(**) US-supplied items; power, commands, and monitors for these units shall be provided by NASA-MMA. Requirements concerning these units shall not be defined in this document.

Figure 3.0-2 shows the CNR/PSN provided Core Equipment block diagram with reference to Table 3.0-1.


SA
Satellite
3-Axis Accelerometer Gyro System
SMS
Tether
Reel Mechanism (MMA)
Deployer/MPESS
DMS
DVG
SETS **
TCVM
TCS
1Ω
*
CEGHS
CEGH1
CEGH2
Aspect *
Magnetometer
DV
CEG

* NASA provided

** TI-provided

```
////////////////////SATELLITE//////////////////////////
  ----------------------------------------------------
  | SCORE:  TAG - TREE-AXIS ACCELEROMETER      (SLA) |
  |             - TREE-AXIS GYRO               (AMCS)|
  ----------------------------------------------------

  ----------------------------------------------------
  | SCORE:  TCVC - CORE TETHER CURRENT MONITOR  (SA) |
  |              - SATELLITE MAIN SWITCH        (SMS)|
  ----------------------------------------------------
///////////////////////// |  ///////////////////////
                          |
                          |     TETHER
                          |
///////////////////////// | //// DEPLOYER/PALLET ////
                          |
             --------------------------
             | REEL MECHANISM IMPEDANCE|
             --------------------------
                          |
   ------------------------------------------------
   | DCORE:  TCVC - DEPLOYER MASTER SWITCH  (DMS) |
   ------------------------------------------------
///////////////////////// | ////////////////////// ////
                          |
///////////////////////// | ////////////// MPESS /////
 -------------------------------------------------------
 | DCORE:  TCVC - TETHER CURRENT SENSOR  (TCS)   to PI |
 -------------------------------------------------------
            |                            |
 ------------------------    --------------------------
 |- CORE TETHER VOLTAGE |    |- CEG HEADS SWITCHING   |
 |  MONITOR  (DV)       |    |  DEVICE  (CEGHS)       |
 ------------------------    --------------------------
           _| _                    |           |
           ///               --------------------------
 ------------------------    |- CEG HEAD  1 & 2       |
 |- VACUUM GAUGE   (DVG)|    |  (CEGH1 & 2)           |
 ------------------------    --------------------------
                           A _| _  C|         C | A_| _
 ------------------------    ///   |           |  ///
 |- POWER DISTRIBUTION  |    --------------------------
 |         &            |    |- FILAMENT & PULSING    |
 |  ELECTRONIC CONTROL  |    |  POWER SUPPLIES 1 & 2  |
 |  UNIT  (DPECU)       |    |   (FPPS1 & 2)          |
 ------------------------    --------------------------
 /////////////////////////////////////////////////////////
```

FIG.3.0-2 PSN/CNR PROVIDED CORE EQUIPMENT BLOCK DIAGRAM

4.0 OPERATIONAL MODES

It should be noticed that for the first TSS mission the only TCVC mode foreseen is the Electron Gun mode as specified in TSS-CER-01. In order to simplify the CEG design for the first TSS mission the Electron beam current will not be controlled by a feedback. The TCVC system will have the primary operational mode described below, which is completely accomodated by the Core Equipment. Additional operational modes can be created with the addition of certain items of PI-supplied hardware. In addition, the Electron Gun Mode should allow ON/OFF pulsing of the Tether current up to 150 mA (TBR) at frequencies up to 1000 Hz.

In this mode, the current path is from the ionospheric plasma down to the Tether through the Satellite conductive skin, the Tether current monitor, and the Satellite Main Switch. Then across the reel mechanism, the Deployer Master Switch, the Tether Current Sensor through the cathode of one of the two CEG heads to the ambient ionospheric plasma (see fig.3.0-1). The anode of the CEG head is connected to the Orbiter electrical ground and the cathode heather is powered by an isolated power supply (floating at the Tether potential). The SETS FPEG operation could avoid orbiter charging due to the CEG anode leakage current. The high voltage for electron acceleration is supplied directly by the emf generated across the Tether by its motion through the geomagnetic field. This emf depends both on the velocity of the Orbiter/Tether system and the effective electrical length of the Tether, which is the component of the Tether length projected across the geomagnetic field. Owing to the dipole structure of the geomagnetic field, there is considerable variation in Tether emf along typical satellite orbits. For a 20 km Tether with a 28.5° inclination orbit similar to that to be used for TSS-1, the range of emf is from about 2000 V up to 5000 V.

4.1 TCVC operational sub-modes

The present section defines the TCVC basic sub-modes of operation listed below:

- Electrodynamic OFF mode (EOFF)
- CEG Standby mode (STB)
- Quiescent Pressure Monitoring (QPM)
- Satellite I-V curve mode (SIVC)
- Low Frequency (1 Hz) Current Pulsing mode (LFCP)
- Medium Frequency (1 kHz) Current Pulsing mode (MFCP)
- PI Current and Voltage measuring mode (PICV)

The status of TCVC units during the above sub-modes is shown in Table 4.0-1.

UNITS \	OPERATIONAL SUB-MODES						
	EOFF	STB	QPM	SICV	LFCP	MFCP	PICV
SCORE:							
SA	OFF	ON	OFF	ON	ON	ON	ON
SMS	CLOSED	CLOSED	CLOSED	CLOSED	CLOSED	CLOSED	CL/OPEN
DCORE:							
DMS	OPEN	CLOSED	OPEN	CLOSED	CLOSED	CLOSED	CLOSED
DV	OFF	ON	OFF	ON	ON	ON	ON
CEGHS:							
SW1	OPEN	OPEN	OPEN	CLOSED $^{(1)}$	CLOSED $^{(1)}$	CLOSED $^{(1)}$	OPEN
SW2	OPEN $^{(1)}$	OPEN	OPEN	CLOSED $^{(1)}$	CLOSED $^{(1)}$	CLOSED $^{(1)}$	OPEN
CEGH:							
Head 1	OFF	OFF	OFF	ON $^{(2)}$	ON $^{(2)}$	ON $^{(2)}$	OFF
FPPS 2	OFF	ON	OFF	ON	ON	ON	OFF
Head 2	OFF	OFF	OFF	ON $^{(2)}$	ON $^{(2)}$	ON $^{(2)}$	OFF
FPPS 2	OFF	ON	OFF	ON	ON	ON	OFF
DVG	OFF	ON	ON	ON	ON	ON	ON
PDECU	OFF	ON	ON	ON	ON	ON	ON

TCVC UNITS STATUS DURING THE OPERATIONAL SUB-MODES

Table 4.0-1

(1) When SW1 in closed SW2 must be open and viceversa;
(2) When one of the two CEG Heads is ON the other is OFF.

4.1.1 Electrodynamic OFF mode (EOFF)

This mode refers to an unpowered status of both the SCORE and DCORE TCVC units, without current flowing down the Tether. The TCVC configuration is with the Satellite Main Switch (SMS) closed, the Deployer Master Switch (DMS) open, and the CEGHS switches open (see Table 4.0-1). This is in order to share the full emf induced voltage (up to 5 kV) among the DMS, CEGHS, and CEG Heads, the Satellite end of the Tether being connected to the Satellite conductive skin and pratically at the same ionospheric plasma potential.

The following functions shall be monitorable from outside:

- Satellite Main Switch status, from RTUP to crew and POCC
- Deployer Master Switch status, from SFMDM to crew and POCC
- CEGHS switches status, from TBD
- DCORE powering status, from STS to crew and POCC.

The TCVC shall enter this mode by external commands from QPM or STB modes via the follwing steps:

1. The PDECU shall receive the external EOFF set command and shall power off:

   a - the CEG heads electronics (FPPS1 and 2)
   b - the DVG
   c - the DV

   and shall output the related OFF monitors;

2. The DMS shall be open;

3. The SMS shall be closed;

4. The SA shall be powered off;

5. The CEGHS switches shall be open;

6. The DCORE main power bus shall be powered off.

Steps 1b and 6 only shall be performed when the TCVC is set into EOFF mode starting from QPM mode.

In case of STS power blackout during any mode, the DCORE TCVC shall be safed as follows:

The CEG heads electronics (FPPS1 & 2), DVG, DV, and the PDECU shall be automatically powered off; the status of the switches (DMS, CEGHS), which is not modified due to their latching type, shall be monitored out.

At STS power blackout end, the PDECU shall automatically reset the DCORE TCVC to STB mode as described in 5.1.2.

In case of TSS-S power bus undervoltage (TS-SR-AI-005) the SCORE shall be safed as follow:

The SA shall be off for the undervoltage duration; the status of the SMS, which is not modified due to its latching type, shall be monitored out.

At TSS-S power bus undervoltage end, the SCORE TCVC shall return automatically to its previous status.

4.1.2 CEG Standby mode (STB)

The TCVC configuration is with all SCORE and DCORE units powered ON, the SMS and DMS closed and the two CEGHS switches open, and the two CEG head filaments cold (see Table 4.0-1). This mode allows the SETS experiment to operate independently from the CEG. In addition the TCVC will provide a slow sampling rate of both the Tether current and Tether-to-Orbiter voltage, and the ambient pressure in the vicinity of the CEG heads. In order to measure the emf induced voltage the SETS experiment must not connect the Tether Current Sensor (TCS) to the Orbiter electrical ground.

This mode can be enterred by the following variuos ways:

- upon external command at power-on events
- automatically (under PDECU control) after any other mode except EOFF
- upon external "override" command if interruption of any other mode is decided.

STB mode onset shall be achieved via the following steps (steps 1 to 3 below shall take place only at power-on):

1. The TCVC shall be powered by the following external commands:
   - to the DCORE power supply (power on, from Crew or POCC)
   - to the SCORE current meter (SA power on, from Crew or POCC)
2. The PDECU shall be directly powered on by the first command, it shall perform its self-check and shall send GO/NOGO information to crew and POCC
3. Upon STB set external command, the PDECU shall power on the DVG, DV and (TBR) the CEG electronics (the CEG filament shall be unpowered).
4. The PDECU shall perform a checkout of the DCORE including, as a minimum, a limited check of each DCORE unit performance, and shall send GO/NOGO information for each checked unit.
5. The PDECU shall output the powering status of each DCORE unit to the Crew and to the POCC; the various instrument outputs shall also be sent by the PDECU to Crew and POCC.
6. The TSS-S OBDH shall be on and shall monitor the SCORE TCVC status and the SA output.

7. The SMS shall be closed by external command from Crew or POCC: the related status monitor shall be sent to Crew and POCC.

8. The DMS shall be closed by external command from Crew and the related status monitor shall be sent to Crew and POCC.

9. The CEGHS switches shall be open and monitored by the PDECU.

4.1.3 Quiescent Pressure Monitoring mode (QPM)

During this mode all the TCVC units will be in the same status as for the EOFF mode with the exception of the DVG, and PDECU which are powered ON (see Table 4.0-1). During the TSS quiescent phases the DVG will support the SETS FPEG operation and will allow the mapping (only during the predeployment) of the ambient gas pressure in the vicinity of the CEG heads. This investigation is needed in order to detect pressure surges to levels at which damage to CEG might occur.

The SCORE TCVC shall be unpowered and unmonitored throughout this mode because the TSS-S is unpowered.

The DCORE TCVC shall enter this mode from EOFF mode only by external commands via the following steps:

1. The DCORE shall be powered on;

2. The PDECU shall be directly powered on by the previous command, it shall perform its self-check and it shall send GO/NOGO information to Crew and POCC;

3. Upon external QPM set command, the PDECU shall power on the DVG;

4. The PDECU shall perform DVG checkout and shall send GO/NOGO information to Crew and POCC;

5. The PDECU shall output to crew and POCC each DCORE unit powering status and the CEGHS switches status;

6. The DVG output shall be sent by PDECU via SFMDM to crew and POCC;

7. The DMS, and CEGHS switches shall be open. The CEG electronics (FPPS1 and 2), and DV shall be unpowered.

The QPM mode shall be terminated by setting the DCORE TCVC into EOFF mode (see 4.1.1).

4.1.4 Satellite I-V Curve mode (SIVC)

The TCVC configuration is with all SCORE and DCORE units powered ON , the SMS, DMS , and one of the two CEGHS switches closed in order to allow current flow down the Tether (see Table 4.0-1). This mode allows Tether current stepping down in the maximum range from 500 mA down to 10 mA. The sequence time shall be less than one minute, due to CEG heat rejection problem, and also in order to minimize emf variations along the TSS orbit for TSS Satellite I-V curve study. The programming of this mode is achieved by a string of commands whose input parameters are identified in Table 4.0-2.

	OPERATIONAL SUB-MODES						
	EOFF	STB	QPM	SICV	LFCP	MFCP	PICV
Mode selection:							
CEG Heads selection:							
ON-Time				TBD	TBD	TBD	
OFF-Time				TBD	TBD	TBD	
Beam current(*):							
step number N:				N	N=M	N=M	
step number M:				M	N=M	N=M	
Number of pulses				TBD	TBD	TBD	

Table 4.0-2

(*) The beam current value for each step number are quoted in Table 4.0-3 for the various sub-modes of operation.

The Core Equipment TCVC shall be set into this mode starting from the STB mode.

The Core Equipment TCVC shall be set into this mode in the following way:

1. The PDECU shall receive the appropriate values for all the parameters listed above by TBD serial external commands from Crew or POCC;
2. The PDECU shall output the DV, DVG and CEG status and measurements to Crew and POCC;
3. The PDECU shall close the selected CEGHS switch and shall then power the CEG filament by external "execute" command from Crew or POCC;
4. The PDECU shall automatically configure the DCORE TCVC into STB mode at the end of this mode sequence by first switching off the CEG filament and then opening its CEGHS switch;
5. If at any time during mode execution the PDECU detects critical pressure increase, critical accelerating voltage decrease or degraded CEG performance (e.g.,critical increase in the CEG Head anode current) it shall automatically configure the DCORE TCVC into STB mode as in point 4 and output a NOGO message to the Crew and POCC; overriding of the automatically set STB shall be possible to crew or POCC;
6. The SCORE TCVC shall be configured as in the STB mode.

4.1.5 Low Frequency (1 Hz) Current Pulsing mode (LFCP)

The TCVC configuration is with all SCORE and DCORE units powered ON , the SMS, DMS , and one of the two CEGHS switches closed in order to allow current flow down the Tether (see Table 4.0-1). This mode allows ON/OFF Tether current modulation in the range from 10 mA to 500 mA at frequencies up to one Hertz with maximum CEG ON-time of one minute (TBR). The maximum frequency limitation is due to the CEG filament control by which the modulation is achieved. In particular, such Tether current modulation will allow Satellite mounted experiments to study both the Tether current associated magnetic field and the space charge region around the Satellite. The programming of this mode is achieved by a string of commands whose input parameters are identified in Table 4.0-2.

The Core Equipment TCVC shall be set into this mode starting from the STB mode.

4.1.6 Medium Frequency (1 kHz) Current Pulsing mode (MFCP)

The TCVC configuration is with all SCORE and DCORE units powered ON , the SMS, DMS , and one of the two CEGHS switches closed in order to allow current flow down the Tether (see Table 4.0-1). This mode allows ON/OFF Tether current modulation in the range from 10 mA up to 150 mA (TBR). This modulation is achieved by CEG grid control. This mode is mainly aimed to investigate the possibility of using the Tether as an antenna for ULF, VLFand ELF waves generation. The programming of this mode is achieved by a string of commands whose input parameters are identified in Table 4.0-2.

The Core Equipment TCVC shall be set into this mode starting from the STB mode.

4.1.7 PI Current and Voltage measurement mode (PICV)

This mode allows the SETS experiments to operate indipendently from the CEG. The TCVC configuration is with all SCORE and DCORE units powered ON with the exception of the two CEG FPPS1 and 2 powered OFF. The SMS can be commanded in close or open status, the DMS is closed, and the two CEGHS switches open (see Table 4.0-1). In addition the TCVC will provide a slow sampling rate of both the Tether current and Tether-to-Orbiter voltage, and the monitoring of the ambient pressure in the vicinity of the CEG heads. In order to measure the emf induced voltage the SETS experiment must not connect the Tether Current Sensor (TCS) to the Orbiter electrical ground.

This mode can be enterred by the following variuos ways:

- upon external command at power-on events
- automatically (under PDECU control) after any other mode except EOFF
- upon external "override" command if interruption of any other mode is decided.

PICV mode onset shall be achieved via the following steps (steps 1 to 3 below shall take place only at power-on):

1. The TCVC shall be powered by the following external commands:
   - to the DCORE power supply (power on, from Crew or POCC)
   - to the SCORE current meter (SA power on, from Crew or POCC)
2. The PDECU shall be directly powered on by the first command, it shall perform its self-check and shall send GO/NOGO information to crew and POCC
3. Upon PICV set external command, the PDECU shall power on the DVG, DV.
4. The PDECU shall perform a checkout of the DCORE including, as a minimum, a limited check of each DCORE unit performance, and shall send GO/NOGO information for each checked unit.
5. The PDECU shall output the powering status of each DCORE unit to the Crew and to the POCC; the various instrument outputs shall also be sent by the PDECU to Crew and POCC.
6. The TSS-S OBDH shall be on and shall monitor the SCORE TCVC status and the SA output.

	CEG BEAM CURRENT VALUE (mA)		
STEP /	SIVC	LFCP	MFCP
Number 1	10	10	10
Number 2	20	20	15
Number 3	30	30	20
Number 4	40	40	25
Number 5	50	50	30
Number 6	60	60	35
Number 7	80	80	40
Number 8	100	100	45
Number 9	150	150	50
Number 10	200	200	55
Number 11	250	250	60
Number 12	300	300	65
Number 13	350	350	70
Number 14	400	400	75
Number 15	450	450	100 (*)
Number 16	500	500	150 (*)

Table 4.0-3

(*) As design goal.

4.2 TAG Operational modes

The present section defines the accelerometer operating modes for the first TSS mission. All Gyro operations shall be dictated by the TSS-S AMCS requirements and will not be part of this document.

4.2.1 Dynamic OFF mode (DOFF)

1. The accelerometer shall be unpowered
2. The accelerometer status shall be monitorable, from RTUP to Crew and POCC.

The SLA shall enter this mode upon external SLA power off command or in case of TSS-S power bus undervoltage for the undervoltage duration. At undervoltage end the SLA shall enter DES mode as described in 4.2.2.

4.2.2 Dynamic Environment Survey mode (DES)

The TAG shall enter this mode from DOFF mode in two ways:

- upon external command at power on;
- automatically after TSS-S power bus undervoltage.

DES mode onset shall be achieved by external command via the following steps (step 1 below shall take place only at power on):

1. The SLA shall be powered on by external command from POCC or Crew via the TSS-S OBDH.

2. The SLA shall automatically perform its thermal conditioning and it shall automatically output ,via OBDH, its own housekeeping data (to Crew and POCC) and acceleration measurements (to POCC).

The DES mode shall be terminated upon DOFF set external (POCC or Crew) command.

4.3 Core Equipment operational profile

The Core Equipment operational profile shall derive from appropriate sequencing of the modes described in section 4.1 and, in parallel, of the modes described in section 4.2.

The Core Equipment mission profile shall be of the kind illustrated below:

TCVC MODE SEQUENCE:

EOFF, [QPM, EOFF] x j, STB,

[(SIVC, STB) x k, (LFCP, STB) x l, (MFCP, STB) x m] x n, EOFF

TAG MODE SEQUENCE:

DOFF, [DOFF, DES] x p, DOFF

where the factors mean j (or k, l, m, n, p)-times repeated mode.

In preparing the mission sequence, the parameters of each mode shall be chosen to ensure overall compatibility with:

- TSS-S, TSS-D, STS operational constraints
- TSS-S & TSS-D resource allocations
- TSS science operational profile.

References

1. D.S. CROUCH and M.M. VIGNOLI Shuttle Tethered Satellite System Development Program AIAA-84-1106

2. A. LORENZONI Development Status of the First TSS Satellite AIAA-86-0052

3. TSS-CER-01 ; BASIC October, 1984 Core Equipment requirements Document

Abbrevations and acronyms

AMCS - Attitude Measurement and Control Subsystem
ASMN - Analog Single Ended Monitor
CEG - Core Electron Generator
CMD - Command
DCC - DC Current
DCORE - Deployer mounted Core Equipment
CEGH1,2 - CEG head 1,2
CEGHS - CEG Head Switching device
CER - Core Equipment Requirements
DES - Dynamical Environment Survey mode
DMS - Deployer Master Switch
DOFF - Dynamic OFF mode
DV - Core Tether Voltage Monitor
DVG - Gas Pressure Monitor
ELF - Extremely Low Frequency
EMC - Electromagnetic Compatibility
EMP - Enhanced MDM Pallet
EOFF - Electrodynamic OFF mode
FPPS1,2 - Filament and Pulsing Power Supplies
FPEG - Fast Pulse Electron Gun
GMT - Greenwich Mean Time
ICD - Interface Control Document
IRD - Interface Requirements Document
KBPS - Kilo Bit Per Second (= 1000 Bit Per Sec)
LFCP - Low Frequency Current Pulsing mode
MFCP - Medium Frequency Current Pulsing mode
MLDT - Memory Load Command
MMA - Martin Marietta Aerospace
MME - SLA Microgravity Measurement Sensor
MMS - SLA Microgravity Measurement Electronics
MNT - Monitor
MPESS - Mission Peculiar Equipment Support Structure
OBDH - On Board Data Handling
PCB - Power Control Box
PCDA - Power and Control Distribution Assembly
PDECU - Power Distribution and Electronic Control Unit
PI - Principal Investigator
PICV - PI Current and Voltage measurement mode
P/L - Payload
PMP - Parts, Materials and Processes
POCC - Payload Operation Control Center
PPDA - Payload Power Distribution Assembly
QPM - Quiescent Pressure Monitoring mode
PTB - Payload Timing Buffer
RDCM - Relay Driving Command
RSMN - Relay Sensing Monitor
RTUP - Payload dedicated Remote Terminal Unit
RTUS - Service dedicated Remote Terminal Unit
SA - Core Tether Current Monitor(Satellite Current Meter)

SCORE - Satellite mounted Core Equipment
SFMDM - Smart Flexible Multiplexer De-Multiplexer
SIVC - Satellite I-V Curve
SLA - Three-Axis Accelerometer
SMS - Satellite Main Switch
SRMN - Serial Monitor
S/S - Sub-System
STB - Standby Mode
STS - Space Transportation System (the Orbiter)
TAG - Three-axes Accelerometer Gyro system
TBD - To Be Defined
TBR - To Be Reviewed
TBV - To Be Verified
TCS - Tether Current Sensor
TCVC - Tether Current Voltage Control system
TCVM - Tether Current and Voltage Measuring devices
TSS - Tethered Satellite System
TSS-D - TSS Deployer
TSS-S - TSS Satellite
ULF - Ultra Low Frequency
VLF - Very Low Frequency

PROGRAM REVIEW OF ELECTRODYNAMIC TETHER RELATED ACTIVITIES AT NASA LEWIS RESEARCH CENTER

JOSEPH C. KOLECKI

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National Aeronautics and
Space Administration
Lewis Research Center

POWER TECHNOLOGY DIVISION

NASA

PROGRAM REVIEW OF ELECTRODYNAMIC TETHER RELATED ACTIVITIES AT NASA LEWIS RESEARCH CENTER

LIST OF ACTIVITIES

- CONCEPTUAL DESIGN OF A 100 KW ELECTRODYNAMIC TETHER SYSTEM.
- MODELLING AND EXPERIMENTAL CHARACTERIZATION OF HOLLOW CATHODES AS PLASMA CONTACTORS.
- BEAM PLASMA INTERACTION STUDIES.
- ATOMIC OXYGEN RESISTANT THIN FILM COATINGS FOR USE ON TETHER INSULATORS.

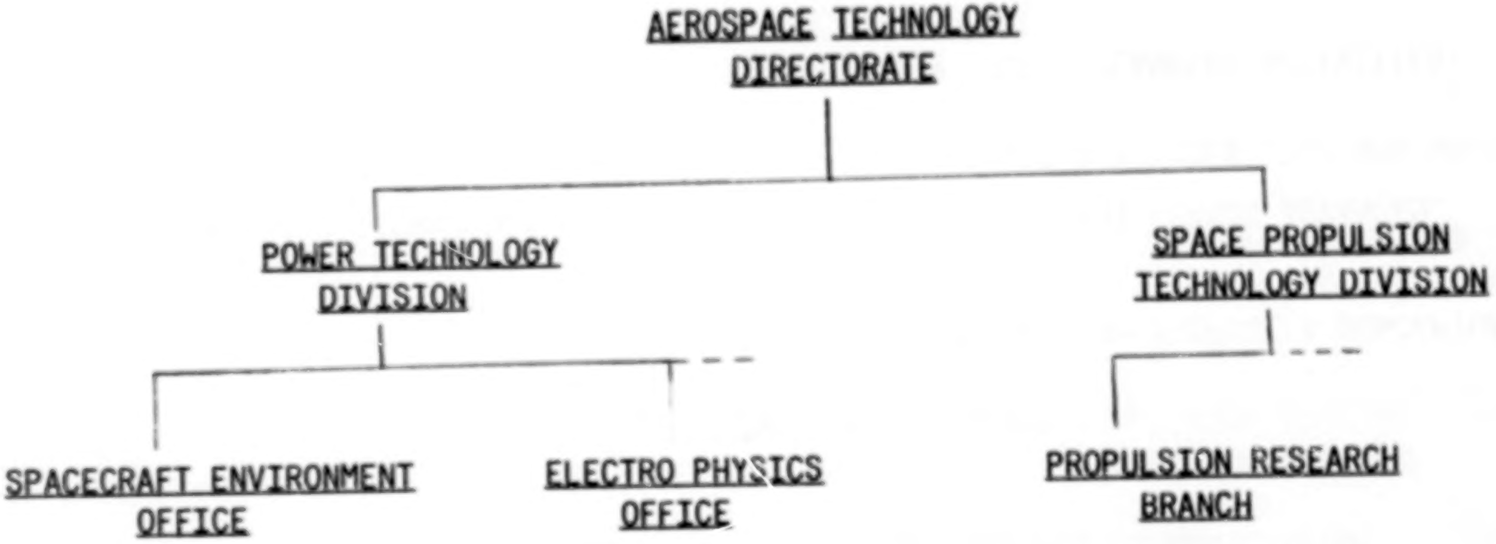
OUT-OF-HOUSE SUPPORT : CONTRACTS AND GRANTS

- MASSACHUSETTS INSTITUTE OF TECHNOLOGY AND SMITHSONIAN ASTROPHYSICAL OBSERVATORY.
- S-CUBED. DIVISION OF MAXWELL LABORATORIES.
- COLORADO STATE UNIVERSITY.
- UNIVERSITY OF ALABAMA IN HUNTSVILLE.
- CLEVELAND STATE UNIVERSITY AND CASE WESTERN RESERVE UNIVERSITY.

National Aeronautics and
Space Administration
Lewis Research Center

POWER TECHNOLOGY DIVISION

NASA LEWIS ORGANIZATION FOR ELECTRODYNAMIC TETHER ACTIVITIES



AEROSPACE TECHNOLOGY DIRECTORATE

POWER TECHNOLOGY DIVISION

SPACE PROPULSION TECHNOLOGY DIVISION

SPACECRAFT ENVIRONMENT OFFICE

ELECTRO PHYSICS OFFICE

PROPULSION RESEARCH BRANCH

National Aeronautics and
Space Administration
Lewis Research Center

POWER TECHNOLOGY DIVISION

NASA

CONCEPTUAL DESIGN OF A 100KW ELECTRODYNAMIC TETHER SYSTEM

OBJECTIVES OF THE STUDY

- IDENTIFY APPLICATIONS. ASSESS ENGINEERING ISSUES AND PROPOSE A CONCEPTUAL DESIGN.
- ESTABLISH TECHNOLOGY REQUIREMENTS : STATE OF THE ART VERSUS ADVANCED.
- MODEL OVERALL SYSTEM BEHAVIOR AT LOW EARTH ORBIT ALTITUDES (200-500 NAUTICAL MILES).
- INTEGRATE RESULTS INTO SPACE STATION POWER SYSTEM PLANNING ACTIVITIES.

CONTRACTOR AND PRINCIPAL INVESTIGATORS

- MASSACHUSETTS INSTITUTE OF TECHNOLOGY AND SMITHSONIAN ASTROPHYSICAL OBSERVATORY.
- PROFESSOR MANUEL MARTINEZ-SANCHEZ (MIT) AND DR. MARIO GROSSI (SAO).

CURRENT PROGRAM STATUS

- CONTRACT NEWLY AWARDED (AS OF END-SEPTEMBER). WORK IS JUST BEGINNING.

MODELLING AND EXPERIMENTAL CHARACTERIZATION OF HOLLOW CATHODES AS PLASMA CONTACTORS

OBJECTIVES

- MODEL PERFORMANCE OF HOLLOW CATHODE AND HOLLOW CATHODE BASED PLASMA CONTACTORS
  - SPACE (LEO) ENVIRONMENT
  - SIMULATED SPACE ENVIRONMENT
- PERFORM GROUND TESTS TO OBTAIN DATA ON THESE DEVICES.
  - COMPARE WITH EXISTING MODELS/USE IN DEVELOPMENT OF NEW MODELS
  - COMPARE WITH SPACE DATA (HITCHHIKER-G. TSS-1).
- OPTIMIZE DEVICE PERFORMANCE AS ELECTRON COLLECTOR/ION EMITTER FOR USE ON POSITIVE END OF ELECTRODYNAMIC TETHER.

CONTRACTORS AND PRINCIPAL INVESTIGATORS

- S-CUBED INC. : DRS. IRA KATZ AND DON PARKS
- COLORADO STATE UNIVERSITY : DR. PAUL WILBUR
- NASA LEWIS : DRS. FRANK BERKOPEC AND MICHAEL PATTERSON. MR. JOSEPH KOLECKI

CURRENT STATUS - MODELLING

- o "ELECTRODYNAMIC TETHER STUDY I - FINAL REPORT, 1984", (COMPLETE).
  - OVERVIEW STUDY OF ELECTRODYNAMIC TETHER SYSTEM WITH STEADY STATE CIRCUIT MODEL, ELECTRON GUN SOURCES, HOLLOW CATHODE PLASMA CONTACTORS, TIME DEPENDENT EFFECTS, EXCITATION OF WAVES, DRAG AND STABILITY AGAINST KINK MODES.
- o "ELECTRODYNAMIC TETHER STUDY II", (FINAL REPORT IN PROGRESS).
  - ELECTRON COLLECTION (AMPS) AS FUNCTION OF MASS FLOW, ELECTRICAL POTENTIAL AND PARTICLE TEMPERATURES.
  - OPTIMAL PERFORMANCE OCCURS FOR ION CURRENTS 1/30 COLLECTED ELECTRON CURRENTS.
  - PREDICTS POTENTIAL vs DISTANCE FOR SPHERICAL COLLECTION WITH CONTACTING PLASMA. RESULT MATCHES EXPERIMENTAL CURVES (REF. COLORADO STATE UNIVERSITY).

C-6

CURRENT STATUS : LABORATORY CHARACTERIZATION

o COLORADO STATE UNIVERSITY:

- EXPERIMENTS IN VACUO WITH HOLLOW CATHODE AND REFRACTORY ELECTRON EMITTING FILAMENT. HOLLOW CATHODE IS BIASED WRT FILAMENT AND CURRENT IS MEASURED AS FUNCTION OF BIAS VOLTAGE.
- OTHER PARAMETERS MEASURED : ION PRODUCTION RATE. ELECTRON DENSITY DISTRIBUTION. PLASMA POTENTIAL.
- DATA INDICATE EXISTANCE OF DOUBLE SHEATH REGION BETWEEN AMBIENT PLASMA AND HIGH DENSITY PLASMA PLUME REGION CLOSE TO HOLLOW CATHODE ORIFACE.
- RECOMMENDS DEVICE OPTIMIZATON BY INCREASING ION PRODUCTION EFFICIENCY.

CURRENT STATUS : LABORATORY CHARACTERIZATION (CONTINUED):

0 NASA LEWIS RESEARCH CENTER

  - VACUUM CHAMBER EXPERIMENTS PERFORMED IN TANDEM WITH COLORADO STATE UNIVERSITY.
  - HOLLOW CATHODE MOUNTED IN VACUO WITH REFRACTORY FILAMENTS AND 30 CM THRUSTER.
  - INITIAL CHARACTERIZATION INVOLVED RUNNING IN SEVERAL DIFFERENT CONFIGURATIONS OF THESE ELEMENTS.
  - RESULTS CONFIRM EFFICACY OF HOLLOW CATHODE AS AN ELECTRON COLLECTOR.
  - RECOMMENDS PARAMETRIC INVESTIGATION TO COVER GEOMETRIC FACTORS AND PLASMA PARAMETERS.

ISSUES

- MODELLING AND ANALYSIS
  - FURTHER EXPLORATION OF 1/30 RATIO BETWEEN ION CURRENT AND COLLECTED ELECTRON CURRENT.
  - EFFECT OF MOTION THROUGH THE MAGNETIC FIELD.
  - MECHANISM OF PARTICLE COLLECTION AT PHYSICAL BOUNDARIES OF THE DEVICE.
  - TYPES AND EFFECTS OF INSTABILITY IN THE PLASMA CLOUD.
- LABORATORY CHARACTERIZATION
  - MEASUREMENTS OF ION PRODUCTION RATE
  - MECHANISM OF PARTICLE COLLECTION AT PHYSICAL BOUNDARIES OF THE DEVICE.
  - DEFINITION OF ION CURRENT TO ELECTRON CURRENT RATIO.
  - MAGNETIC FILED EFFECTS.
  - EFFECTS OF DEVICE GEOMETRY.

BEAM PLASMA INTERACTION STUDIES

OBJECTIVES

- INVESTIGATE SPACECRAFT CHARGING DATA FROM SCATHA SATELLITE.
  - SATELLITE AT LOCAL MIDNIGHT IN SUNLIGHT AT GEOSYNCHRONOUS ALTITUDE.
  - 50V ELECTRON BEAM (10-100μA) FIRED AWAY FROM SATELLITE WAS ACCOMPANIED BY A PEAK IN THE RETURN FLUX AT 70 eV.
  - SEPAC EXPERIMENTS (SPACELAB I, NOV. AND DEC., '83) PRODUCED SIMILAR RESULTS/DATA NOT EXTENSIVELY ANALYSED YET, EXCEPT FOR WORK DONE BY KATZ ET AL.
- MATHEMATICALLY MODEL CHARGING BEHAVIOR OF HIGH ALTITUDE SATELLITES VIA NASCAP CODE.
- COMPARE ANALYSED OPERATIONS WITH BASIC BEAM-PLASMA DISCHARGE THEORY AND KATZ'S SPACE CHARGE OSCILLATION THEORY.

PRINCIPAL INVESTIGATOR

- UNIVERSITY OF ALABAMA IN HUNTSVILLE : DR. R.C. OLSEN.

CURRENT STATUS

- WORK IN PROGRESS.

ATOMIC OXYGEN RESISTANT THIN FILM COATINGS FOR USE ON TETHER INSULATOR

OBJECTIVES

- DEVELOP FLEXIBLE. OXYGEN RESISTANT THIN FILM COATINGS FOR PROTECTION OF TETHER INSULATORS.
- DEMONSTRATE REEL TO REEL IN VACUO COATING TECHNIQUES NECESSARY TO APPLYING FILMS TO LONG TETHERS.
- ESTABLISH AEROSPACE INDUSTRY CAPABILITY TO FABRICATE PROTECTED THETHER INSULATORS.

CONTRACTORS AND PRINCIPAL INVESTIGATORS

- CLEVELAND STATE UNIVERSITY
- CASE WESTERN RESERVE UNIVERSITY
- NASA LEWIS : MS. SHARON RUTLEDGE. MR. BRUCE BANKS

CURRENT STATUS

- LABORATORY FACILITIES DESIGNED AND PARTIALLY BUILT.
- EARLY LABORATORY RESULTS COMPLETE.

SUMMARY

- o ELECTRODYNAMIC TETHER PROGRAM AT NASA/LeRC INVOLVES A NUMBER OF ACTIVITIES IN AREAS AT CENTER EXPERTISE.
    - MULTIKILOWATT ELECTRICAL POWER SYSTEMS
    - CONTACT WITH ENVIRONMENT/ENVIRONMENTAL INTERACTIONS
    - DEVICE EVALUATION AND DEVELOPMENT
    - MATERIALS CHARACTERIZATION AND DEVELOPMENT
- o POSITIVE RESULTS IN MANY AREAS HAVE ALREADY BEEN OBTAINED.
- o LOOKING FORWARD TOWARD ACTIVE COLLABORATIVE PARTICIPATION IN ADDRESSING NEW ISSUES.

N86-28429

PLASMA CONTACTOR PERFORMANCE CHARACTERIZATION

Paul Wilbur

1. Simplified schematic of Plasma Coupling process under conditions where excessive currents are being demanded and a double sheath region develops with attendant high voltage drops. This condition should be avoided by designing the plasma source (plasma contactor) so it produces adequate plasma. The key to high plasma densities is a high ion production rate.

2. Plasma contactor performance objectives - This transparency should be self-explanatory.

3. The basic elements of the hollow cathode are shown. Electrons are drawn from the insert by field-enhanced thermionic emission and from the bulk plasma by multistep ionization processes. The bulk plasma is sustained by the expellant gas flow through the cathode tube and orifice plate in the presence of the electrical discharge between the cathode insert and anode. Electrons escape from the cathode interior through the orifice; ions are drawn to the insert and orifice place surfaces where they deposite energy, heating these surfaces. Some ions are produced downstream of the orifice as a result of electron collisions with neutral atoms close to the orifice. Electron or ion currents (J_e) can be drawn from this plasma downstream of the orifice to a plasma further downstream of the hollow cathode assembly on demand and depending upon the cathode to downstream plasma potential difference. For present tests a 0.6 cm diameter cathode with 0.6 mm diameter orifice was used.

4. In order to augment the production of ions the hollow cathode based plasma source was designed and built. Key features of this device are:

- a hollow cathode
- an anode moved downstream from the location used for the basic hollow cathode
- an enclosure that confines the neutral gas

- a reverse feed expellant flow plenum
- a ring cusp magnetic field configuration

For the test results presented the basic hollow cathode and the hollow cathode based plasma source used an identical hollow cathode.

5. The ion filings map for the hollow cathode based plasma source. The magnetic field is used to confine ions and electrons and thereby improve ion production performance.

6. The mechanical schematic of the system being used to study the ion and emission characteristics of the hollow cathode (shown) or the hollow cathode based plasma source.

7. The system used to supply power and make electrical measurements in this experiment. The anode supply shown supplies the discharge power. The tank supply is used to bias the hollow cathode or hollow cathode based power source relative to the vacuum tank so ion or electron currents can be drawn to the tank.

8. Typical comparison of the ion/electron emission characteristics of the two devices. The power cited is the discharge power. Either device produces high electron emission currents at modest collector bias conditions. (This situation was observed at all discharge power and expellant flow rate conditions with either argon or xenon expellants.) The hollow cathode based plasma source is a much more effective ion producer than the hollow cathode. The ion current tends to level off at what will be called the ion production rate at sufficiently negative potentials (~ - 30 V for the case shown). The term SCCM means standard cubic centimeters/minute.

9. The effects of discharge power and expellant flow are shown. Ion production rates are over an order of magnitude better for the hollow cathode based plasma source than for the basic hollow cathode. The hollow cathode based plasma source operates better (more efficiently) when the bulk of the expellant is fed through the main flow plenum.

10. When argon is used in place of xenon in either device, the performance of that device is degraded.

11. Expellant utilization (fraction of input expellant that leaves the source in an ionized state) vs. the energy cost of a plasma ion that escapes the source is a typical plot that characterizes ion production performance. These curves also show the hollow cathode based plasma source is a much more efficient ion source than the hollow cathode itself for the case of xenon expellant.

12. When argon is used the hollow cathode based plasma source again shows substantially better performance than the basic hollow cathode.

13. A broadly defined performance comparison of the hollow cathode and hollow cathode based plasma source based on the experiments reported is given. This comparison is based on performance goals cited in 2. The comparison suggests substantial gains in ion production capability for the hollow cathode based plasma source for a very modest increase in ion source complexity.

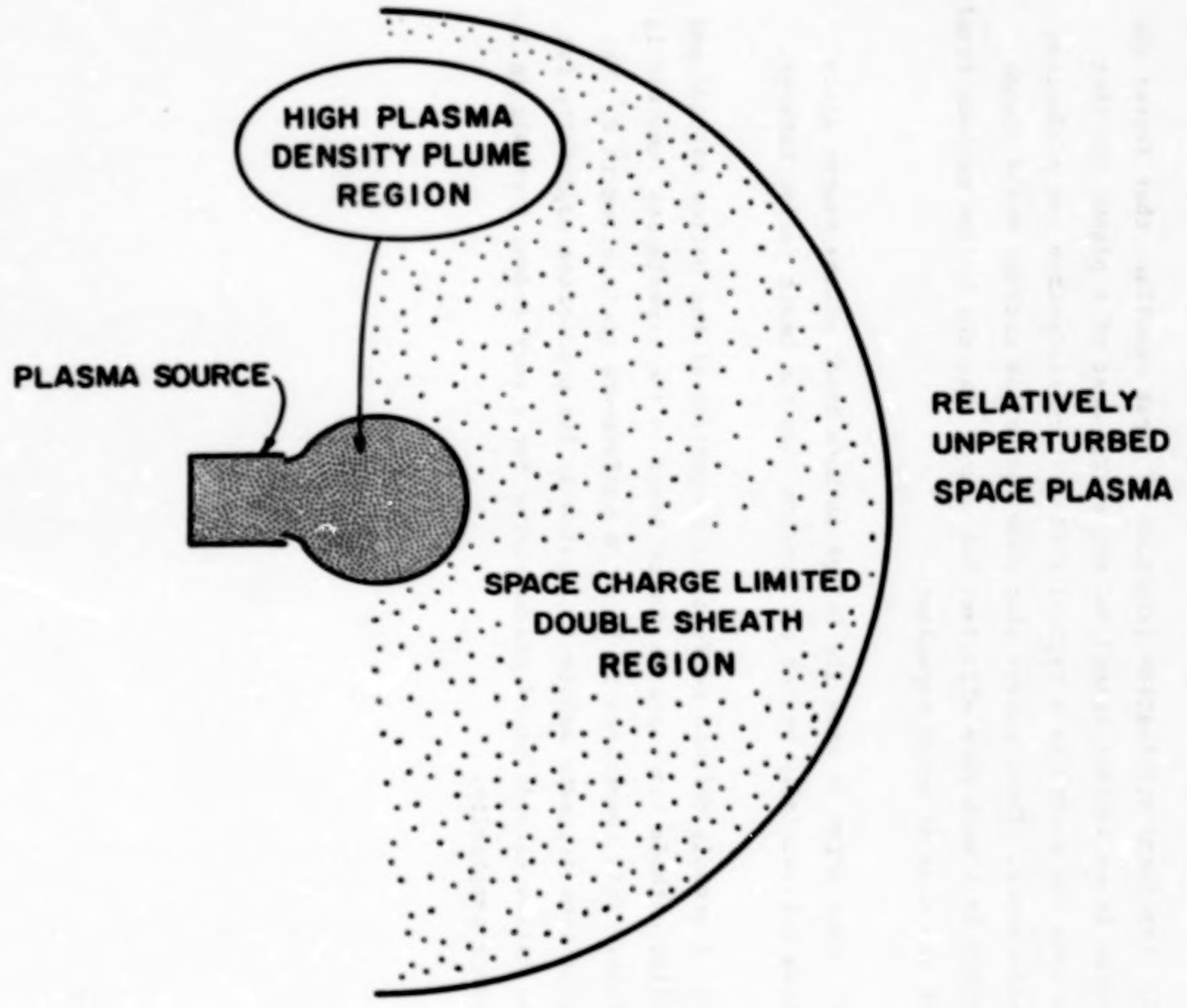
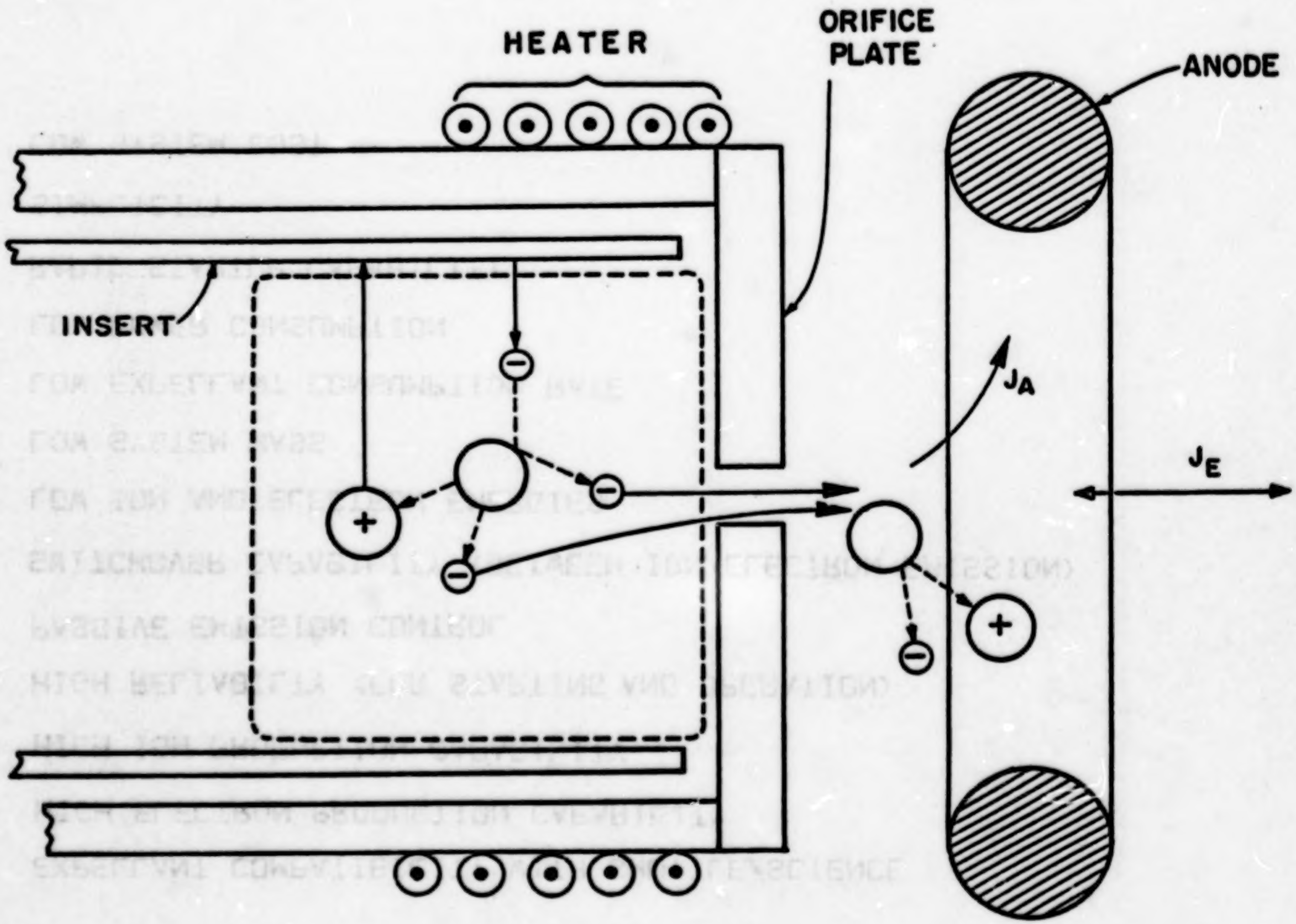

HIGH PLASMA DENSITY PLUME REGION
PLASMA SOURCE
SPACE CHARGE LIMITED DOUBLE SHEATH REGION
RELATIVELY UNPERTURBED SPACE PLASMA

Figure 1

PLASMA CONTACTOR PERFORMANCE OBJECTIVES

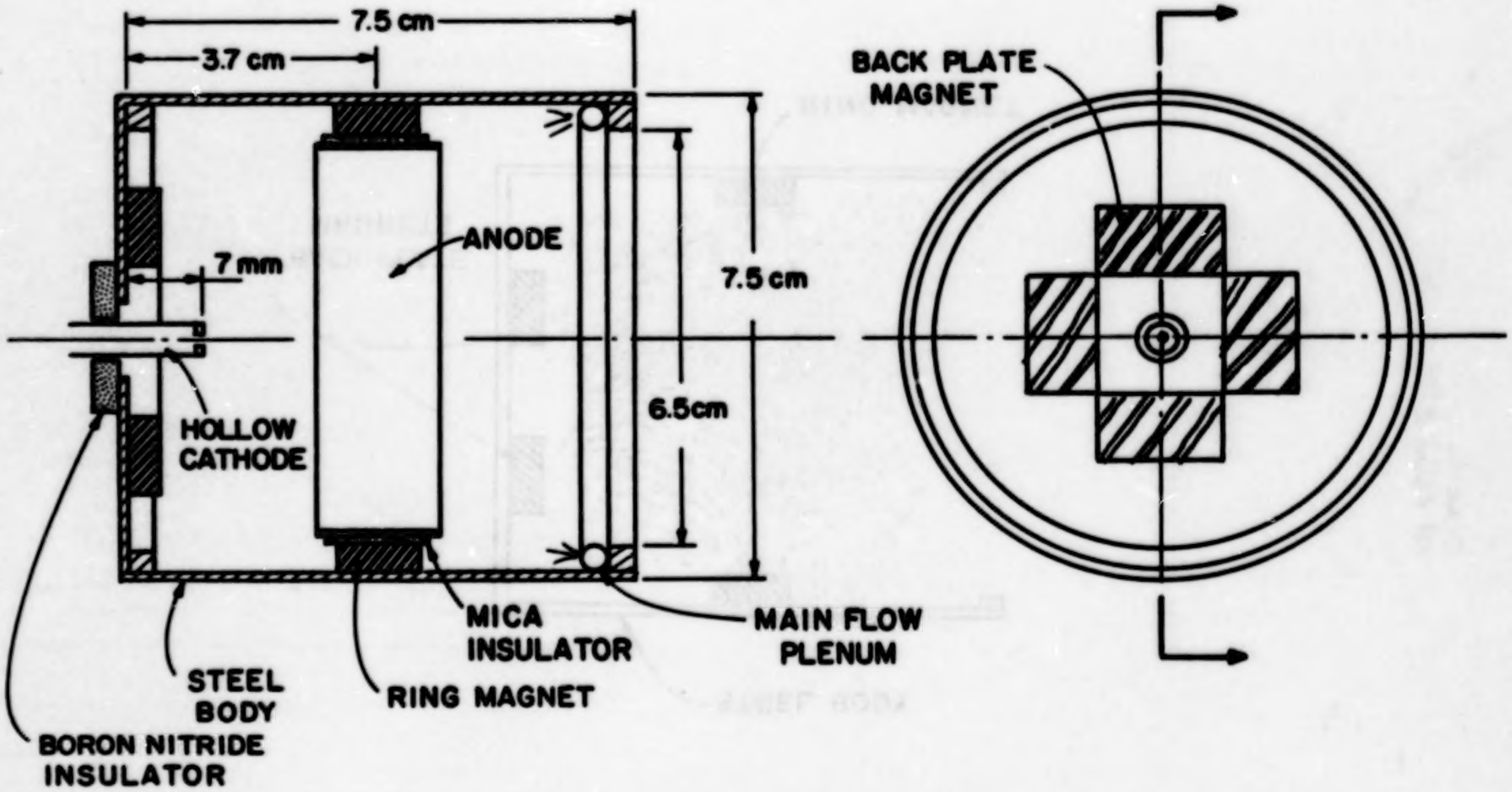
- EXPELLANT COMPATIBILITY WITH SHUTTLE/SCIENCE
- HIGH ELECTRON PRODUCTION CAPABILITY
- HIGH ION PRODUCTION CAPABILITY
- HIGH RELIABILTY (FOR STARTING AND OPERATION)
- PASSIVE EMISSION CONTROL
- SWITCHOVER CAPABILITY (BETWEEN ION/ELECTRON EMISSION)
- LOW ION AND ELECTRON ENERGIES
- LOW SYSTEM MASS
- LOW EXPELLANT CONSUMPTION RATE
- LOW POWER CONSUMPTION
- RAPID STARTUP CAPABILITY
- SIMPLICITY
- LOW SYSTEM COST

Figure 2


HEATER
ORIFICE PLATE
ANODE
INSERT
J_A
J_E
+
−
−
−
−
+

HOLLOW CATHODE ASSEMBLY

Figure 3


7.5 cm
3.7 cm
7 mm
ANODE
7.5 cm
6.5cm
BACK PLATE MAGNET
HOLLOW CATHODE
MICA INSULATOR
MAIN FLOW PLENUM
STEEL BODY
RING MAGNET
BORON NITRIDE INSULATOR

HOLLOW CATHODE BASED
PLASMA SOURCE

Figure 4

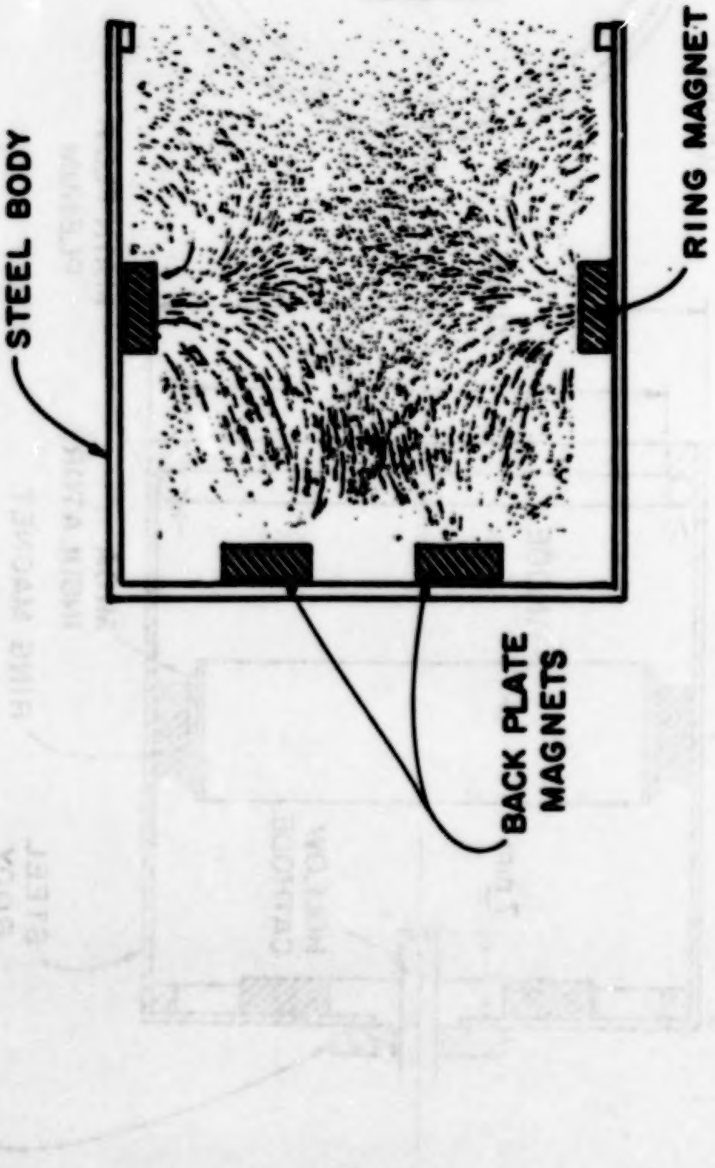
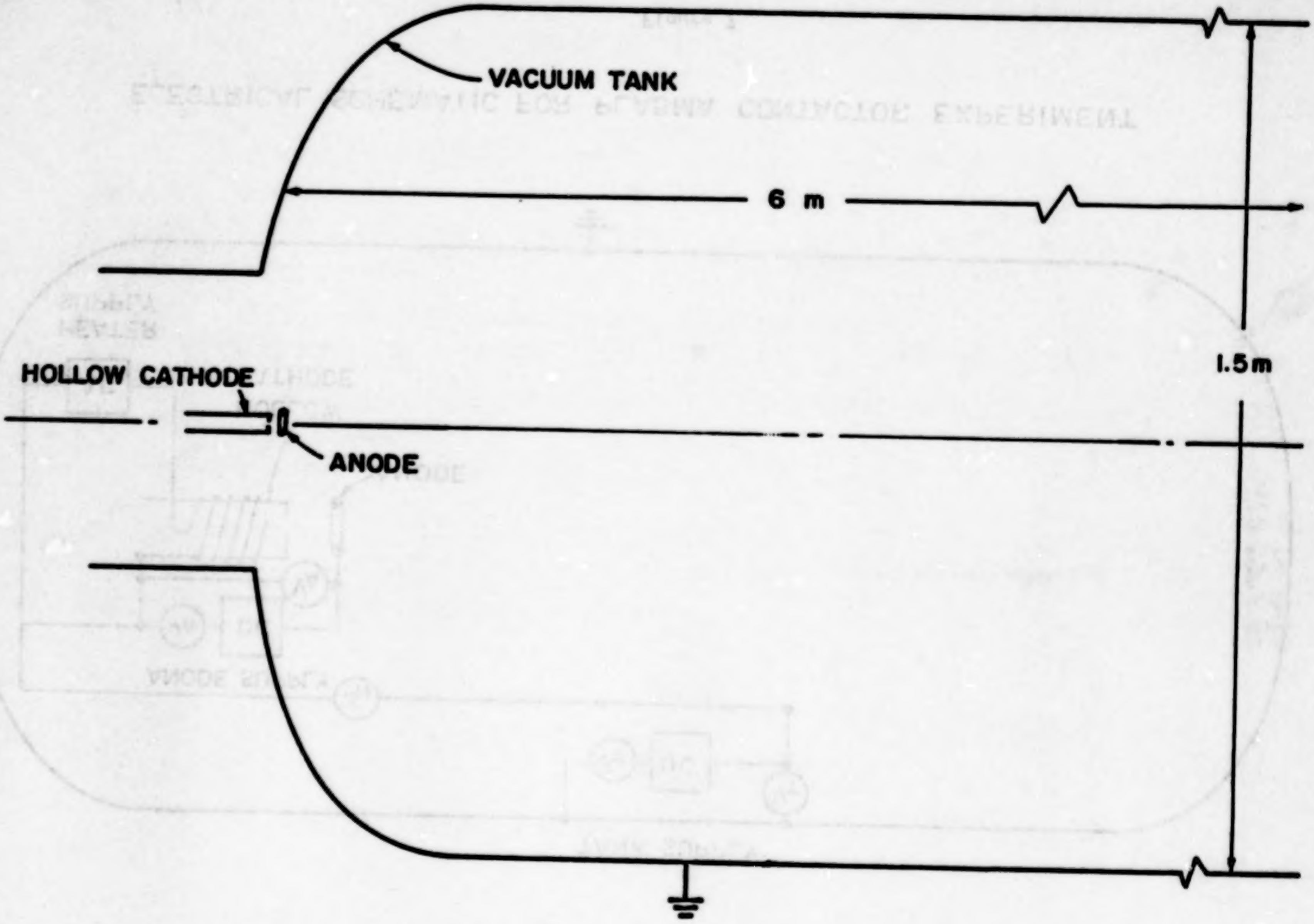
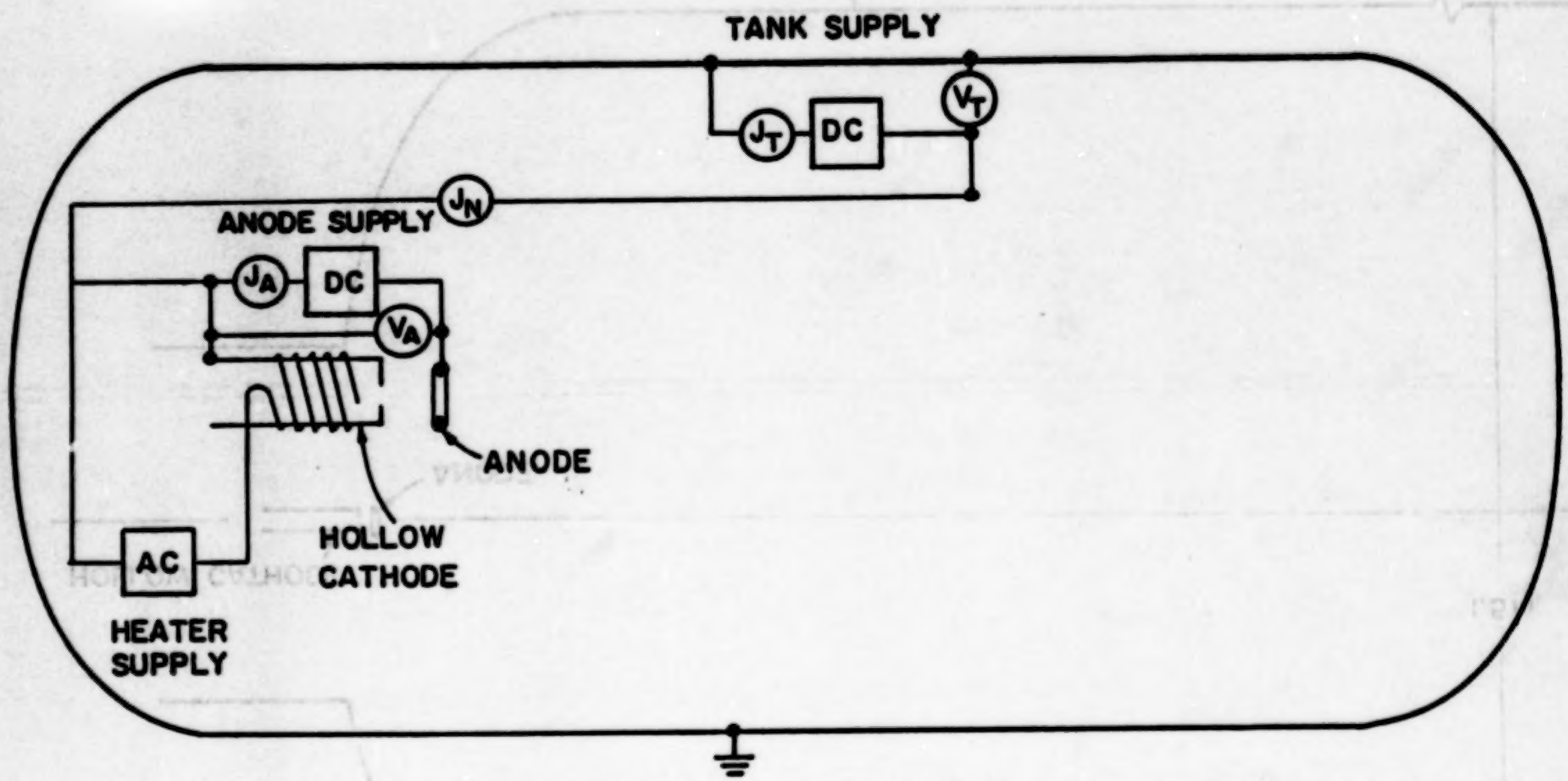

STEEL BODY
RING MAGNET
BACK PLATE MAGNETS

Figure 5


VACUUM TANK
6 m
1.5 m
HOLLOW CATHODE
ANODE

MECHANICAL SCHEMATIC FOR PLASMA CONTACTOR EXPERIMENT

Figure 6

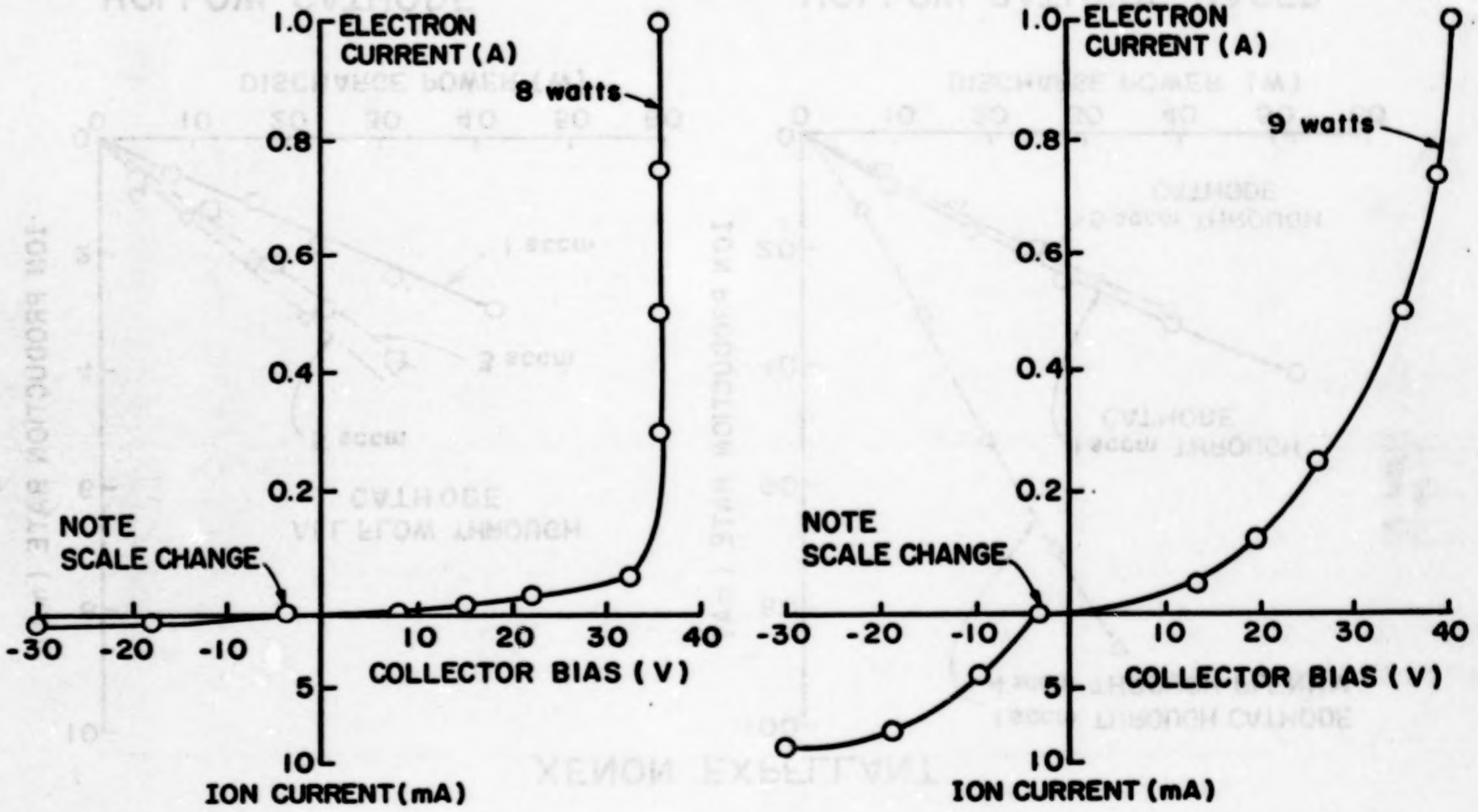

TANK SUPPLY
J_T
DC
V_T
J_N
ANODE SUPPLY
J_A
DC
V_A
ANODE
HOLLOW CATHODE
AC
HEATER SUPPLY

ELECTRICAL SCHEMATIC FOR PLASMA CONTACTOR EXPERIMENT

Figure 7

XENON EXPELLANT

1 sccm THROUGH CATHODE



HOLLOW CATHODE

HOLLOW CATHODE BASED PLASMA SOURCE

Figure 8

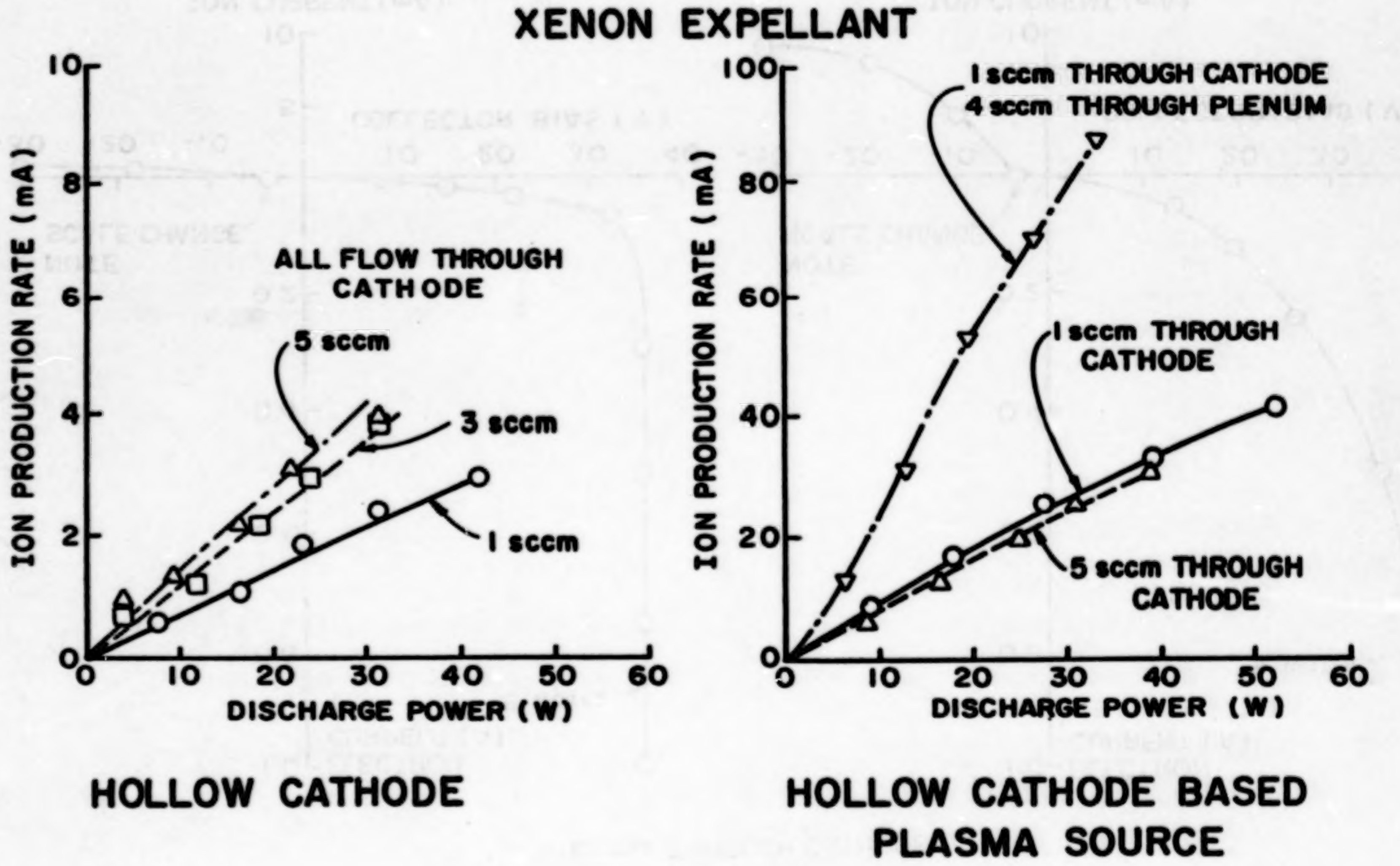
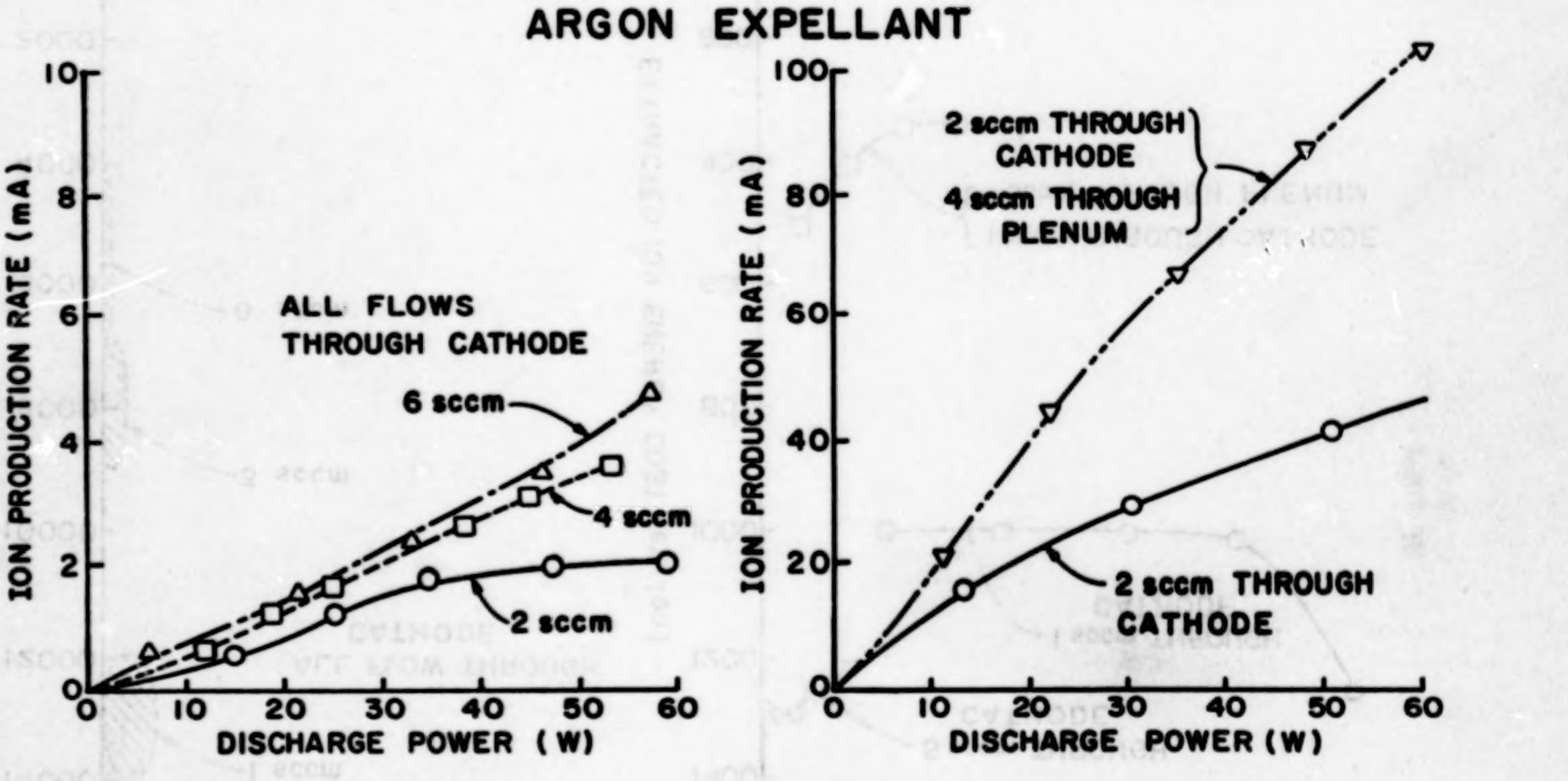

XENON EXPELLANT
ION PRODUCTION RATE (mA)
10
8
6
4
2
0
DISCHARGE POWER (W)
0
10
20
30
40
50
60
ALL FLOW THROUGH CATHODE
5 sccm
3 sccm
1 sccm
HOLLOW CATHODE
ION PRODUCTION RATE (mA)
100
80
60
40
20
0
DISCHARGE POWER (W)
0
10
20
30
40
50
60
1 sccm THROUGH CATHODE
4 sccm THROUGH PLENUM
1 sccm THROUGH CATHODE
5 sccm THROUGH CATHODE
HOLLOW CATHODE BASED PLASMA SOURCE

Figure 9



HOLLOW CATHODE

HOLLOW CATHODE BASED PLASMA SOURCE

Figure 10

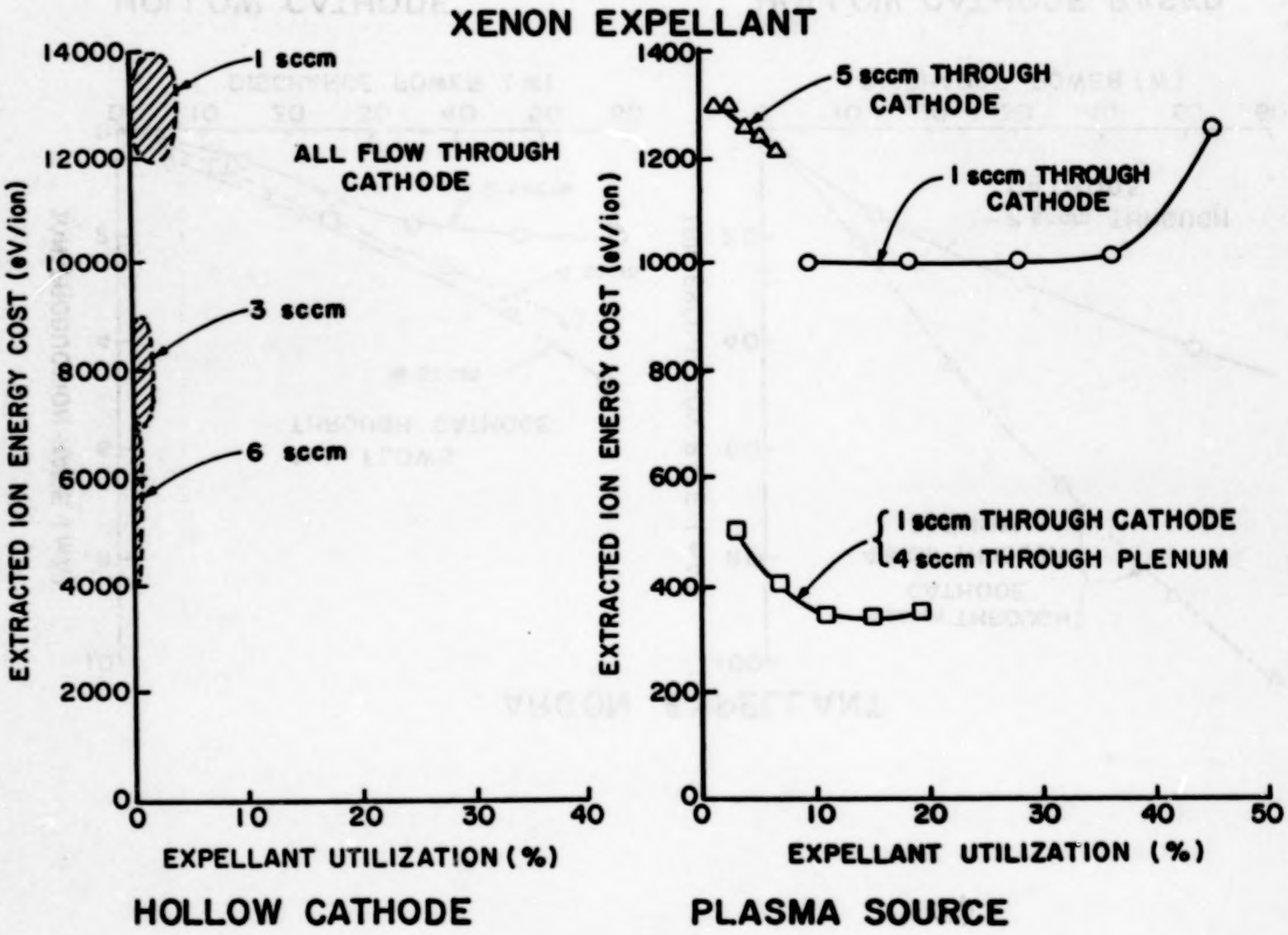
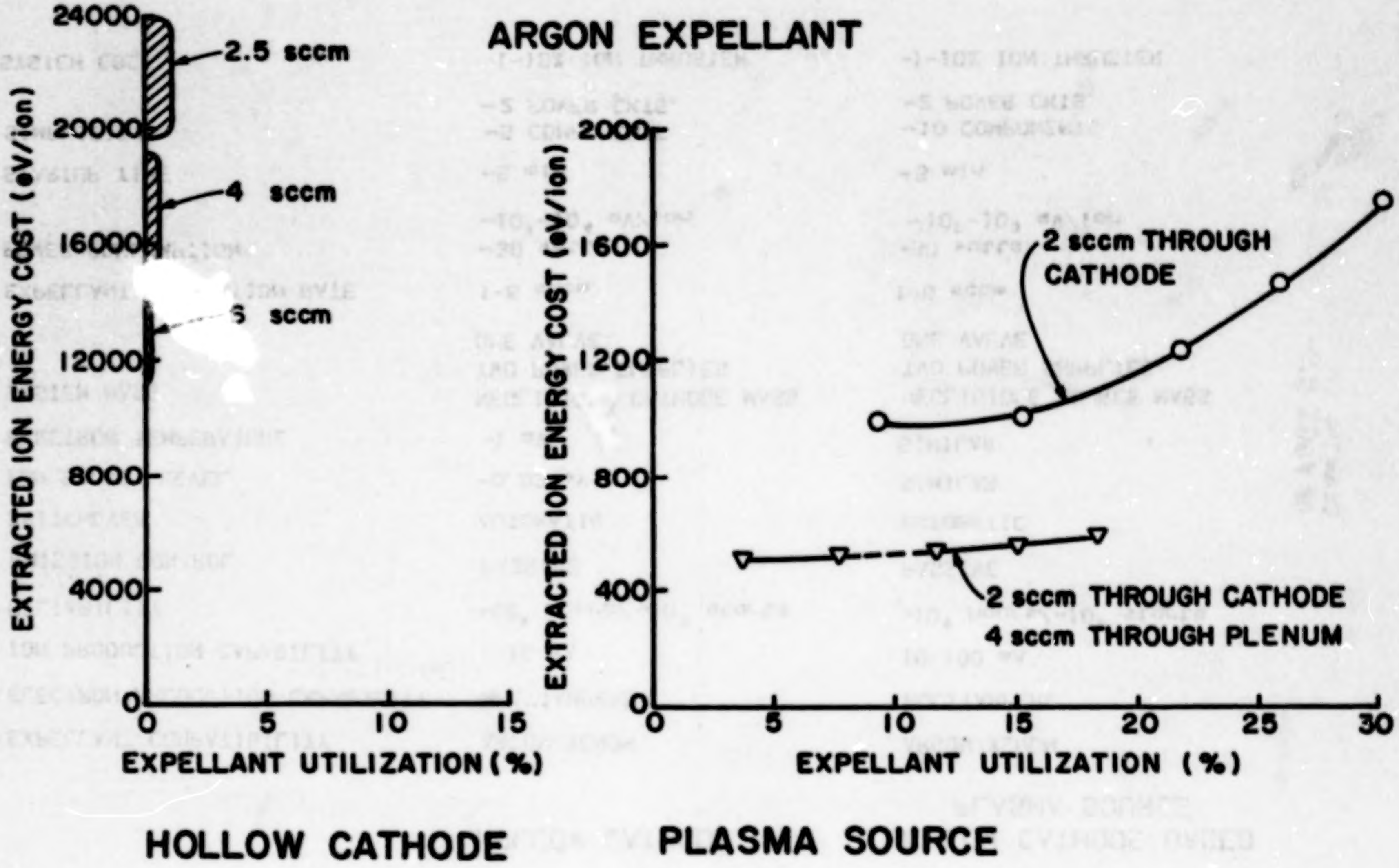

XENON EXPELLANT
EXTRACTED ION ENERGY COST (eV/ion)
14000
12000
10000
8000
6000
4000
2000
0
1 sccm
3 sccm
6 sccm
ALL FLOW THROUGH CATHODE
0
10
20
30
40
EXPELLANT UTILIZATION (%)
HOLLOW CATHODE
EXTRACTED ION ENERGY COST (eV/ion)
1400
1200
1000
800
600
400
200
0
5 sccm THROUGH CATHODE
1 sccm THROUGH CATHODE
1 sccm THROUGH CATHODE
4 sccm THROUGH PLENUM
0
10
20
30
40
50
EXPELLANT UTILIZATION (%)
PLASMA SOURCE

Figure 11


ARGON EXPELLANT

HOLLOW CATHODE

PLASMA SOURCE

Figure 12

PLASMA CONTACTOR PERFORMANCE COMPARISON

	HOLLOW CATHODE	HOLLOW CATHODE BASED PLASMA SOURCE
• EXPELLANT COMPATIBILITY	ARGON/XENON	ARGON/XENON
• ELECTRON PRODUCTION CAPABILITY	MULTIAMPERE	MULTIAMPERE
• ION PRODUCTION CAPABILITY	1-10 mA	10-100 mA
• RELIABILITY	~10^4 hours/~10^3 starts	~10^4 hours/~10^3 starts
• EMISSION CONTROL	PASSIVE	PASSIVE
• SWITCHOVER	AUTOMATIC	AUTOMATIC
• ION ENERGY LEVEL	~0.03 eV	SIMILAR
• ELECTRON TEMPERATURE	~1 eV	SIMILAR
• SYSTEM MASS	NEGLIGIBLE CATHODE MASS TWO POWER SUPPLIES ONE VALVE	NEGLIGIBLE SOURCE MASS TWO POWER SUPPLIES ONE VALVE
• EXPELLANT CONSUMTION RATE	1-6 sccm	1-6 sccm
• POWER CONSUMPTION	~30 watts ~10^3-10^4 eV/ion	~30 watts ~10^2-10^3 eV/ion
• STARTUP TIME	~5 min	~5 min
• SIMPLICITY	~5 COMPONENTS ~2 POWER CKTS.	~10 COMPONENTS ~2 POWER CKTS.
• SYSTEM COST	~1-10% ION THRUSTER	~1-10% ION THRUSTER

Figure 13

S-CUBED
A Division of Maxwell Laboratories, Inc.

THEORY OF PLASMA CONTACTORS FOR ELECTRODYNAMIC TETHERED SATELLITE SYSTEMS

D. E. Parks and I. Katz
S-CUBED

Presented at

Second Biennial Workshop
Applications of Tethers in Space
Venice, Italy

October 15-17, 1985

N86-28430

THEORY OF PLASMA CONTACTORS FOR ELECTRODYNAMIC TETHERED SATELLITE SYSTEMS*

D. E. Parks and I. Katz
S-CUBED
P. O. Box 1620, La Jolla, CA 92038

ABSTRACT

Recent data from ground and space experiments indicate that plasma releases from an object dramatically reduce the sheath impedance between the object and the ambient plasma surrounding it. Available data is in qualitative accord with the theory developed below to quantify the flow of current in the sheath. Electron transport in the theory is based on a fluid model of a collisionless plasma with an effective collision frequency comparable to frequencies of plasma oscillations. The theory leads to low effective impedances varying inversely with the square root of the injected plasma density. To support such a low impedance mode of operation using an argon plasma source for example, requires $I_p - I_e/30$; that is, only one argon ion must be injected for each thirty electrons extracted from the ambient plasma. The required plasma flow rates are quite low; to extract one ampere of electron current requires a mass flow rate of about one gram of argon per day.

INTRODUCTION

The electrodynamic tethered satellite system requires the ejection of electrons from the shuttle at one end of the system and the collection of a compensating current by the satellite at the other end. While the simplest concept is to collect electrons on the subsatellite and to collect a corresponding number of positive ions on the shuttle orbiter, ion collection by the orbiter is acknowledged to be inadequate to support the desired levels of current. The baseline configuration has an electron gun mounted on the shuttle. To obtain ampere sized currents, assuming a perveance of 6×10^{-6} amperes/volt$^{3/2}$, requires thousands of volts across the gun. This voltage drop corresponds to an effective emission impedance of thousands of ohms. An alternative method of emitting electrons from the shuttle is creating a high density plasma in the vicinity of the shuttle. Calculations presented below show sheath impedances are dramatically reduced by the use of hollow cathode plasma sources.

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* This work supported by NASA/Lewis Research Center, Cleveland, OH 44135 under Contract No. NAS3-23881.

Passive collection of ampere level electron currents by the tethered satellite is simple in concept; however, there is also a substantial sheath impedance associated with the flow of charge between the tethered satellite and the ambient space plasma environment. Theory[1] predicts that the extraction of amperes of electron current by a sphere of 1.5 meter diameter requires a potential of kilovolts. This high impedance collection is in substantial accord with the results of the Plasma Interaction Flight Experiment (PIX)[2] which collected only a few milliamperes of current with a kilovolt bias on a 2000 cm^2 solar panel. Both theory and flight data demonstrate clearly the need to increase the current flow between the TSS and the space plasma.

One way to collect more electrons is to increase the diameter of the tethered satellite, but this is impractical for TSS-1. Another way is to increase the plasma current in the vicinity of the subsatellite. This can be done by mounting a plasma source, such as a hollow cathode, on the subsatellite. The SEPAC electron beam experiments conducted on Space Lab I indicate plasma sources to be an effective means for neutralizing beam currents and controlling spacecraft potentials.[3] When a plasma cloud was ejected along with a 5 keV, 0.3 amp electron beam, the spectrum of returning electrons was confined to energies below the beam energy, and the orbiter potential was clamped to a small value on the order of 1 volt. When the plasma jet was not active, however, the electron energy spectrum developed a peak at 1.1 keV and there were significant fluxes of electrons above the primary beam energy. The SEPAC experiments provide clear evidence of the low impedance neutralization of a high current electron beam by a plasma plume.

The next section gives a brief review of some properties of hollow cathode sources. The following sections develop a model for estimating the impedance to current flow across the plasma produced by the hollow cathode source, and determines the rate of plasma production required to support a low impedance mode of current collection.

HOLLOW CATHODE PLASMA SOURCES

One device for generating a contactor plasma is the hollow cathode. Hollow cathode devices have played a prominent role in space applications, especially in the development of ion thrusters for solar electric propulsion systems. Ion beams ejected by ion accelerators were charge and current neutralized by electron currents flowing from the cathode through the plasma generated by the hollow cathode. The concept of the hollow cathode as a beam neutralizer was successfully incorporated into the SERT II satellite, and performed in space flight tests in the manner expected on the basis of tests conducted in high vacuum laboratory facilities.[4]

The hollow cathode is a compact, low impedance device. The simplified features of one such device are indicated schematically in Figure 1.[5]

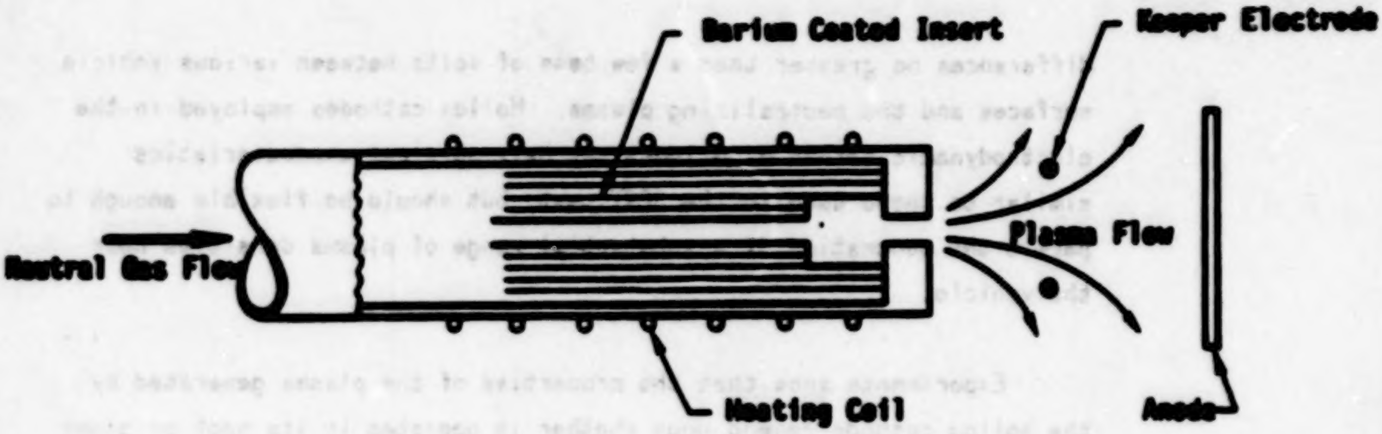

Figure 1. Schematic diagram of a hollow cathode configuration.[5]

A neutral gas, such as mercury or argon, flows into the cathode chamber where it is ionized by field accelerated electrons emitted from the coated insert or chamber walls through thermionic or other processes. The keeper electrode assists in initiating and in stabilizing the electrical discharge. With these devices nearly complete ionization of the neutral gas can be achieved, the resulting plasma flowing through the orifice at the net upstream flow rate. Various devices of this type have been operated at mass flow rates ranging from micrograms per second to grams per second, with currents ranging from milliamperes to kiloamperes.[5,6,7] For applications to the electrodynamic tethered satellite system, primary interest attaches to the low flow rate, low current range.

The hollow cathode used in the SERT experiment had a length of about 10 cm, an external diameter of about one-half centimeter and an orifice diameter of about 1 mm. It used Hg as the operating gas. Mercury flow rates of the order of 100 ma equivalent, or less, neutralized beam currents of order of 250 ma, while developing potential differences no greater than a few tens of volts between various vehicle surfaces and the neutralizing plasma. Hollow cathodes employed in the electrodynamic tether experiment may have physical characteristics similar to those used in the SERT test, but should be flexible enough to permit the generation of a substantial range of plasma densities near the vehicle.

Experiments show that the properties of the plasma generated by the hollow cathode depend upon whether it operates in its spot or plume mode.[5] More complete ionization, higher plasma densities and electron temperatures, and a lower electrical impedance of the discharge generally characterize the spot mode. The plume mode is characterized by less efficient ionization, a lower plasma density and a higher electrical impedance to the flow of discharge current than the spot mode. A higher rate of gas flow, shorter cathode to anode distance and a higher discharge current tend to produce the spot mode. Figure 2 shows an example of a measured discharge voltage current characteristic.[7]

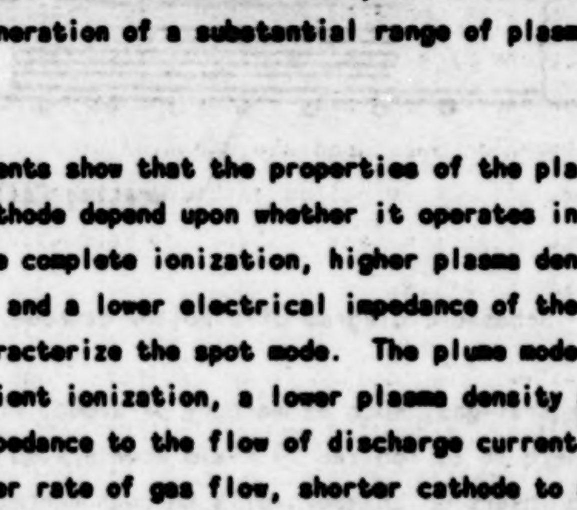

Figure 2. Discharge voltage-current characteristic.

HOLLOW CATHODES AS ELECTRON EMITTERS

Hollow cathodes have been used as plasma sources in ground test facilities and in space flight tests to charge and current neutralize ion beams of solar powered ion propulsion systems. In the space flight tests electrons were transported long distances from their source along the path of neutralized high energy ion beams. There have not been experiments which bear upon the question of how effectively electron currents may flow from hollow cathode sources into the ambient plasma in the absence of an ion beam. Thus, the conclusions reached below must be regarded as tentative.

Experiments conducted in ground facilities indicate that the plasma, despite long classical collisional mean free paths, appears to behave in a resistive manner.[8,9,10] Previous calculations of neutralizer plasmas showed that, at least for regions of several centimeters from the cathode orifice, the plasma properties and electron current flow patterns conformed to a fluid model of electron transport.

The basic elements of the model are the steady state ion continuity and momentum equations

$$\nabla \cdot n\vec{V} = 0 \tag{1}$$

$$M \frac{d\vec{V}}{dt} = e\left(E + \frac{\vec{V}\times\vec{B}}{c}\right) - \frac{\nabla p_i}{n} \tag{2}$$

where $n = n(\vec{r})$ is density of ions of mass M at the position $\vec{r}$ and $\vec{V}$ their mean velocity. The motion of the ion is influenced by the ambient magnetic field $\vec{B}$, the ion pressure p_i (both set to zero in previous studies), and the electric field in the quasineutral plasma. Quasineutrality, together with the assumption that electrons issuing from the cathode orifice satisfy the momentum balance equation

$$\nabla p_e + en\vec{E} = n\eta e\vec{j} \tag{3}$$

relating the electron pressure,

$$p_e = n\theta \tag{4}$$

the electric field, and the net current density $\vec{j}$. Here θ is the electron temperature in energy units and η is the resistivity. If the plasma is non-resistive, $\eta = 0$, and isothermal, Eq. (3) yields the Boltzmann law

$$n = \exp(e\phi/\theta) \tag{5}$$

relating the density and the electric potential. In general the plasma resistivity η is related to an effective collision frequency ν by

$$\eta^{-1} = \frac{ne^2}{m} \nu^{-1} \tag{6}$$

where m is the electron mass and where for a sufficiently dense and cold plasma ν is the classical electron ion collision frequency. If the plasma is not collision dominated, randomization of electron velocities may still occur through enhanced levels of fluctuating electric fields, such as occur in the unstable passage of electron streams through the plasma. These mechanisms are effective in coupling hollow cathode electrons into the plasma at effective collision frequencies that may be almost as large as the plasma frequency.[8] When augmented by an energy balance equation, two-dimensional calculations predict temperatures and potentials in reasonable agreement with ion engine neutralization data obtained both in the laboratory and in space.

This theory for electron transport can be applied in simplified form to electron emission to the space plasma. Consider a spherical source with its center chosen as the origin of a coordinate system. The plasma is assumed isothermal, and its density through space given by

$$n = \frac{n_o r_o^2}{r^2} \tag{7}$$

to a distance R where $n = n_{amb}$;

$$R = r_o \left(\frac{n_o}{n_{amb}}\right)^{1/2} \tag{8}$$

From Eq. (3)

$$\theta \, \nabla n - ne \, \nabla \phi = \eta nej = \eta ne \frac{I}{4\pi r^2} \tag{9}$$

where I is the total current transported to the ambient plasma ($I < 0$ for net electron flow outward).

Integrating

$$- \frac{\theta}{e} \ln \frac{n_o}{n_{amb}} + \phi(r_o) = \frac{I}{4\pi} \int_{r_o}^{R} \eta(r) \frac{dr}{r^2} \tag{10}$$

For a collisionless plasma, η is greatest for strong turbulence, and the effective collision frequency ν is[11]

$$\nu = \alpha \, \omega_p \tag{11}$$

where α is a number of order unity and $\omega_p = \sqrt{4\pi n_e^2/m}$ is the plasma frequency.

Utilizing Eq. (6) and the density given by Eq. (7), we obtain

$$\phi_o(r_o) = \theta \ln \frac{n_o}{n_{amb}} + 9\times10^{11} \frac{\alpha I_{amp}}{r_o \omega_p(r_o)} \frac{1}{2} \ln \frac{n_o}{n_{amb}} \tag{12}$$

with r_o in cm and ω_p in $\sec^{-1}$. The resistive contribution to the impedance is

$$Z = 9\times10^{11} \frac{\alpha}{r_o \omega_p(r_o)} \frac{1}{2} \ln \frac{n_o}{n_{amb}} \text{ ohms} \tag{13}$$

The hollow cathode,[7] operating in the spot mode at a flow rate of 100 mA equivalent, produced an electron density of about 10^{12} cm^{-3} at about 1 cm from the orifice. Taking $r_o = 1$ cm, $n_o = 10^{12}$ cm^{-3}, and $n_{amb} = 10^6$ cm^{-3},

$Z = 23$ ohms

for $\alpha = 0.1$. Previous studies with this model required $\alpha \sim 0.1$, the value $\alpha = 1$ probably corresponds to an overestimate. The magnitudes of resistance given above with $\alpha \sim 0.1$ appear consistent with measurements made over the much shorter paths of current conduction involved in laboratory facilities.

Increasing the density n_o of the injected plasma by two orders of magnitude reduces R by a factor of ten. At densities greater than about 10^{12} cm^{-3} with $\theta \lesssim 1$ eV, classical scattering should be taken into account, however, since the mean free paths for Coulomb scattering are short ($\lesssim 1$ cm at $n = 10^{12}/\text{cm}^3$).

HOLLOW CATHODES AS ELECTRON COLLECTORS

A sphere whose diameter is much greater than a Debye length will collect an electron current greater than the plasma thermal current into the collector's area by attracting electrons across a space charge limited sheath. To collect a strongly enhanced current the potential on the sphere must be much larger than the plasma temperature, i.e., $e\phi \gg \theta$. The current voltage characteristic of such a configuration is well described by the theory of Langmuir and Blodgett.

Most descriptions of the passive collection of electrons by the tethered satellite are based upon space charge limited sheath theory with some modifications due to magnetic field and presheath effects.[12-14] The theory presented here addresses the changes in the potential structure that occur when a plasma is generated in the vicinity of the sphere. This theory omits the effect of a magnetic field, an omission not totally justified, especially in regions where the electron cyclotron frequency is comparable to or greater than the local plasma frequency.

There is little data on the use of hollow cathode plasma sources to enhance electron collection. Theoretical considerations, however, support what limited data there is: the effective impedance of an electron collecting probe is greatly reduced by copious emission of plasma. Even though the theory is incomplete, it identifies the regimes of impedance reduction and defines values of the plasma generation rate which will produce substantial changes in the impedance. Increasing the plasma generation rate, I_p, first reduces the voltage drop across the space charge limited collection sheath, further increases collapse the space charge sheath, and, when the ion generation rate is increased beyond the electron collection rate I_e, current is transported by the ions.

In fact the different regimes of current collection may be categorized according to the following inequalities between ion generation rate I_p and electron collection rate I_e:

Regime I:

$$I_p < \sqrt{\frac{m_e}{m_i}}\, I_e$$

Regime II:

$$\sqrt{\frac{m_e}{m_i}}\, I_e < I_p < I_e$$

Regime III:

$$I_p > I_e$$

Each of these regimes is considered below. For convenience, the collecting sphere is assumed to operate at a constant current.

Regime I.

For a null ion generation rate, current collection (B = 0) is well understood and requires large voltages to extract current much in excess of the geometrical limit. The effect of generating a small amount of plasma at the sphere is approximately equivalent to emitting ions from the anode of a diode. The effect of the electrons created in the ionization process can be ignored if the rate of plasma production is much less than the collected electron current. The plasma ions stream out across the sheath, cancelling a portion of the electron space charge. For planer diodes it has been shown[15] that the maximum ion current density that the sheath can extract is related to the electron current density by

$$j_i = \sqrt{m_e/m_i}\, j_e \, . \qquad (14)$$

This relation, known as the "Langmuir condition", is also the basic stability condition for a strong plasma double layer. At this ion current, the voltage required to sustain a fixed electron current is reduced by one-third. For nonplanar geometries this current ratio can be exceeded by factors of order two. The resulting small reduction in sheath voltage is of little importance compared with the dramatic change that occurs when the plasma generation rate increases beyond the j_i of the double layer stability condition which separates regimes I and II.

Regime II.

Recent calculations of the effect of ionization in electron collecting sheaths have shown that when the "Langmuir condition" ion current is exceeded, the generated plasma remains quasineutral and the ions expand hydrodynamically.[16] In the limit of the plasma generation rate large compared with the "Langmuir condition" ion current, and assuming constant temperature, the potential profile can be described by the Boltzmann law, Eq. (5). The ion density is determined by the self-consistent motion in the quasineutral field. The resultant description of the potentials and densities is the same as that for hollow cathode neutralizers used as electron emitters. What is not certain is the magnitude of the electron transport coefficients. The model described in the previous section for electron emission can serve as a first estimate of electron collection from the ambient plasma. From Eq. (13) the collection area enhancement possible while maintaining isothermal quasineutrality can be obtained by substituting for the total current in terms of the ambient thermal current times an effective collection area, i.e.,

$$I = j_o \, 4\pi R^2. \qquad (15)$$

For a collector radius, a, of one meter, this estimated collector area exceeds the geometric area by the factor

$$\frac{R^2}{a^2} = \frac{r_o^2}{a^2} \, \frac{n_o}{n_{amb}}$$

Taking $r_o = 1$ cm, and $n_o/n_{amb} = 10^6$

$$\frac{R^2}{a^2} = 100$$

Further study is necessary to determine the accuracy of this collection area enhancement.

The plasma generation rate required to sustain this lower impedance mode of electron collection can be estimated as follows. At the effective collection radius R defined by Eq. (15), the ion current from the plasma source is

$$I_i = 4\pi R^2 j_i = 4\pi R^2 n_i V_i ,$$

and since $n_i \cong n_e$, where n_e is the ambient density

$$I_i = 4\pi R^2 n_e V_i = I_e \frac{V_i}{V_e}$$

where V_e is the thermal speed of ambient electrons and V_i is the speed of source ions at the effective collection radius R. As indicated schematically in Figure 3, the net movement of ions is down the potential hill separating the collector from the ambient plasma.

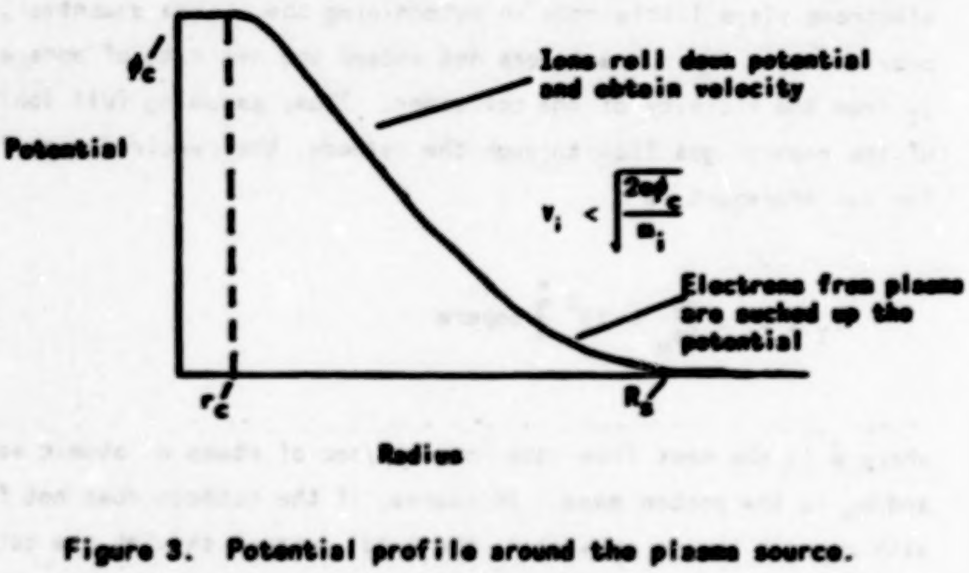
ϕ_c'
Potential
Ions roll down potential and obtain velocity
$v_i < \sqrt{\frac{2e\phi_c}{m_i}}$
Electrons from plasma are sucked up the potential
r_c'
R_s
Radius

Figure 3. Potential profile around the plasma source.

Neglecting the effect of drag, ions starting from rest would attain the maximum velocity $(2e\ \phi_c/m_i)^{1/2}$, so that

$$I_p < I_e(m_e e\phi_c/m_i\theta)^{1/2}$$

and the bound on the required ion current varies only as the square root of the potential. From Eq. (12) and the discussion following it, electron currents near one ampere would correspond to potentials $\phi_c \sim 10$ volts. For an argon plasma, with $\sqrt{m_i/m_e} \sim 300$, and for $\theta \sim 0.1$ eV

$$I_p \le \frac{I_e}{30}$$

Regime III.

For plasma generation rates in excess of the collected currents the net electron current is outward from the subsatellite. In this case the ions transport the current and the effective mobility of the electrons plays little role in determining the plasma potential, provided that the current does not exceed the net rate of escape of ions I_i from the vicinity of the collector. Thus, assuming full ionization of the neutral gas flow through the cathode, the required mass flow rate for ion transport is

$$I_i \le I_p = \frac{\dot{m}}{A m_H} = 10^5 \frac{\dot{m}}{A} \text{ ampere}$$

where $\dot{m}$ is the mass flow rate in grams/sec of atoms of atomic weight A and m_H is the proton mass. Of course, if the cathode does not float with respect to the collector, the total current through the cathode may exceed I_i, but any current through the cathode-collector-plasma loop does not flow through the tether. It is useful to observe that $I_p = 1$ ampere corresponds to a flow rate slightly less than A grams per day. Since high ionization efficiencies are achievable with hollow cathode sources operating in their spot modes it is unlikely that such flow rates for the duration of TSS-1 would significantly impact the satellite mass.

CONCLUSION

For both the electron emitting and electron collecting ends of the tethered satellite system, locally generated plasmas eliminate the space charge sheath. The high voltages necessary to transport charge across a space charge sheath makes the sheath regions the highest impedance portions of the tether system. Reducing this impedance by local plasma sources, such as hollow cathodes, will greatly enhance the effectiveness of a tethered satellite system. While parts of the theory are not yet fully developed and magnetic fields have not been included, the theory does provide a framework for understanding how currents flow through the locally generated plasmas. The theory predicts the impedance for electron emission from the orbiter as a function of plasma generation rate, I_{plasma}; tether current, I_{tether}; and ambient plasma density. For electron collection by the subsatellite, the theory predicts three different collection regimes:

I. $I_{plasma} < \sqrt{\frac{m_e}{m_i}}\, I_{tether}$, High impedance space charge limited collection

II. $\sqrt{\frac{m_e}{m_i}}\, I_{tether} < I_{plasma} < I_{tether}$, Resistive quasineutral transport of electrons

III. $I_{tether} < I_{plasma}$, Low impedance ion transport

Electron emission and all modes of electron collection are well within the capabilities of present technology hollow cathode plasma sources. Regime II is of primary interest, permitting low impedance electron collection for low plasma production rates. For a plasma emitted into the ionosphere in low earth orbit the ion production rate I_p required to extract a current I_e from the ambient plasmas satisfies $I_p \lesssim I_e/30$.

REFERENCES

1. Al'pert, Ya.L., A. V. Gurevich and L. P. Pitaevski, Space Physics with Artificial Satellites, Consultants Bureau, New York, 1965.

2. Mandell, M. J., I. Katz, G. A. Jongeward and J. C. Roche, "Computer Simulation of Plasma Electron Collection by PIX-II," AIAA-85-0386, AIAA 23rd Aerospace Sciences Meeting, Reno, NV, 1985.

3. Reasoner, D. L., J. L. Burch and T. Obayashi, "Analysis of Electron Spectra Produced by SEPAC Plasma Interactions," EOS, Trans. Am. Geophys. Union, 65, p. 1042m 1984.

4. Jones, S. G., J. V. Staskus and D. C. Byers, "Preliminary Results of Sert II Spacecraft Potential Measurements Using Hot Wire Emissive Probes," NASA TM-X-2083, 1970.

5. Csiky, G. A., "Measurements of Some Properties of a Discharge from a Hollow Cathode," NASA Technical Note, NASA-TN-D-4966, February 1969.

6. Knishnan, M., R. G. John, W. F. von Jaskowsky and K. E. Clark, "Physical Processes in Hollow Cathodes," AIAA Journal, 15, P. 1217, 1977.

7. Siegfried, D. E. and P. J. Wilbur, "An Investigation of Mercury Hollow Cathode Phenomena," AIAA/DGLR 13th International Electric Propulsion Conference, San Diego, CA, p. 78, April 1978.

8. Parks, D. E., M. J. Mandell and I. Katz, "Fluid Model of Plasma Outside a Hollow Cathode Neutralizer," J. Spacecraft and Rockets, 19, p. 354, 1982.

9. Katz, I., J. J. Cassidy, M. J. Mandell, D. E. Parks, G. W. Schnuelle, P. R. Stannard and P. G. Steen, "Additional Application of the NASCAP Code. Vol. II, SEPS, Ion Thruster Neutralization and Electrostatic Antenna Model," NASA CR-165350, February 1981.

10. Ward, J. W. and H. J. King, "Mercury Hollow Cathode Plasma Bridge Neutralizers," J. Spacecraft, 10, p. 1161, 1968.

11. Ichimaru, S., Basic Principles of Plasma Physics, A Statistical Approach, Benjamin/Cummings, London, p. 292, 1973.

12. Parks, D. R., I. Katz, G. A. Jongeward and M. Rotenberg, "Electrodynamic Tether Study," S-CUBED Final Report (Draft), SSS-R-85-6883, September 1984.

13. Grossi, M. and D. A. Arnold, "Engineering Study of the Electrodynamic Tether as a Spaceborne Generator of Electric Power," Smithsonian Astrophysical Observatory, SAO Technical Report, NASA Contract NAS8-35497, June 1984.

14. Arnold, D. A. and M. Dobrowolny, "Transmission Line Model of the Interaction of a Long Metal Wire with the Ionosphere," Radio Science, 15, p. 1149, 1980.

15. Langmuir, I., "The Interaction of Electron and Positive Ion Space Charges in Cathode Sheaths," Phys. Rev., 33, p. 954, 1929.

16. Cooke, D. L. and I. Katz, "Ionization Induced Instability in an Electron Collecting Sheath," S-CUBED Report, May 1985.

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THEORY OF PLASMA CONTACTORS
FOR
ELECTRODYNAMIC TETHERED
SATELLITE SYSTEMS

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PRESENTED AT

SECOND BIENNIAL WORKSHOP
APPLICATIONS OF TETHERS IN SPACE

VENICE, ITALY

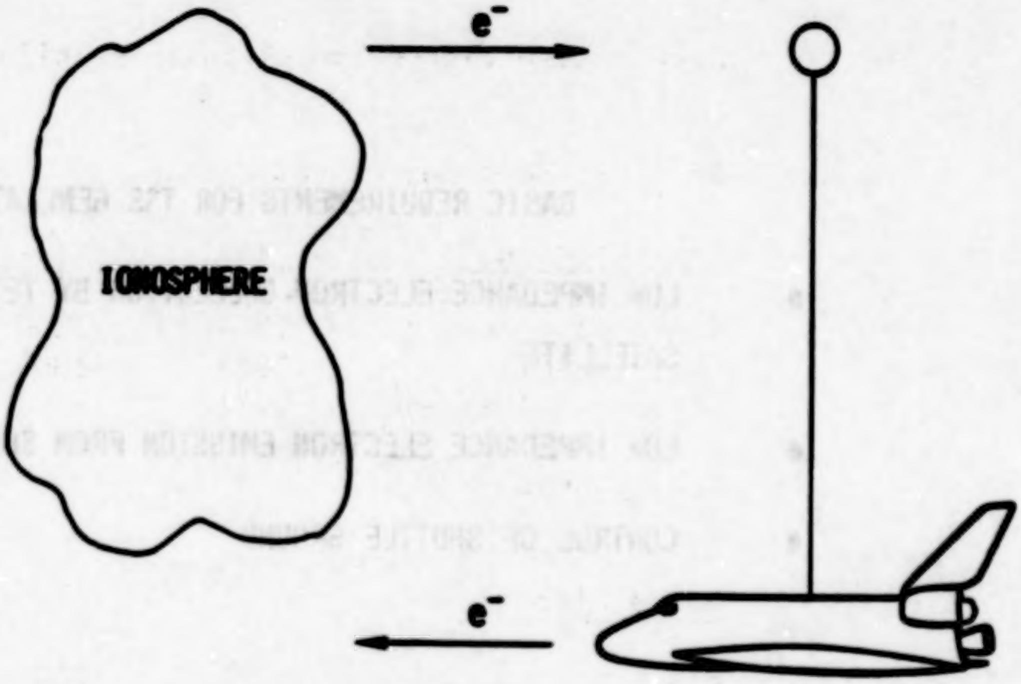
OCTOBER 15-17, 1985

P. O. Box 1620, La Jolla, California 92038-1620
(619) 453-0060

BASIC REQUIREMENTS FOR TSS GENERATOR

- LOW IMPEDANCE ELECTRON COLLECTION BY TETHERED SATELLITE
- LOW IMPEDANCE ELECTRON EMISSION FROM SHUTTLE
- CONTROL OF SHUTTLE GROUND

ELECTRODYNAMIC TETHER CIRCUIT



Transport of electrons to subsatellite and from orbiter determine the magnitude of the tether current.

HIGH VOLTAGE ARCING

- Solar arrays always arc at high negative potentials
- Have caused disruption of power supplies
- This has been demonstrated both in

Lab Experiments	Year	Voltage
Kennerud - Boeing	1974	-1000 V
Chaky - TRW	1983	-1000 V
Snyder - NASA/LeRC	1984	-600 V
Many others		
Space Flights		
PIX I and II		-250 - 1000 V

- Arcing is not restricted to solar arrays

SPACE DATA ON ELECTRON COLLECTION

- **PIX II** 2000 cm^2 $V_{max} = 1000$ Volts $Z_{eff} \doteq 300{,}000\,\Omega$

  $n_e = 10^4$ $I_{max} = 3$ ma

  (800 km)

- **SPACELAB I** 68 m^2 $V_{max} \doteq 1000$ Volts $Z_{eff} \doteq 10{,}000\,\Omega$

  $n_e \sim 10^5$ $I_{max} \doteq 100$ ma

- For shuttle altitudes and above, classical collection appears valid

HOW WELL DO OTHER CONTACTORS WORK

- **ELECTRON GUN EMITTER**

  PERVEANCE = 6×10^{-6} amp/volt$^{3/2}$

  FOR 1 AMPERE

  $V = 3000$ volts

  $Z_{eff} \cong 3000$ ohms

- **PASSIVE 1.5 METER SPHERE COLLECTOR**

  SPACE CHARGE LIMITED, $n_e = 10^6$

  $V_{sat} = 2500$ volts

  $Z_{eff} \cong 2500$ ohms

  with magnetic field, $Z_{eff} \cong 6000$ ohms

  SPACE CHARGE LIMITED, $n_e = 10^5$,

  $Z_{eff} \cong 8000$ ohms

  with magnetic field, $Z_{eff} \cong 50{,}000$ ohms

PREVIEW OF IMPORTANT RESULTS USING PLASMA SOURCES

- LOW IMPEDANCE HIGH CURRENT ELECTRON EMISSION
  - TENS OF OHMS
- LOW IMPEDANCE ELECTRON COLLECTION
  - $I_e \sim 30\ I_p$
- LOW MASS FLOW REQUIREMENTS
  - 1 AMP ELECTRON COLLECTION REQUIRES ~1 gm/day ARGON PLASMA GENERATION RATE

IMPORTANCE OF PLASMA CONTACTORS
FOR
ELECTRODYNAMIC TETHERS

- INCREASE CURRENTS DRIVEN IN IONOSPHERE
- FEASIBILITY OF SPACE POWER SYSTEMS
- TEST NEUTRALIZATION OF SPACECRAFT FOR CHARGED PARTICLE BEAM EMISSION

THEORY OF PLASMA CONTACTORS

- Collision lengths very long, debye lengths very short. Plasma dominated by collective effects.

- Experiments suggest the plasma is turbulent.

OUR APPROACH

- Fluid model

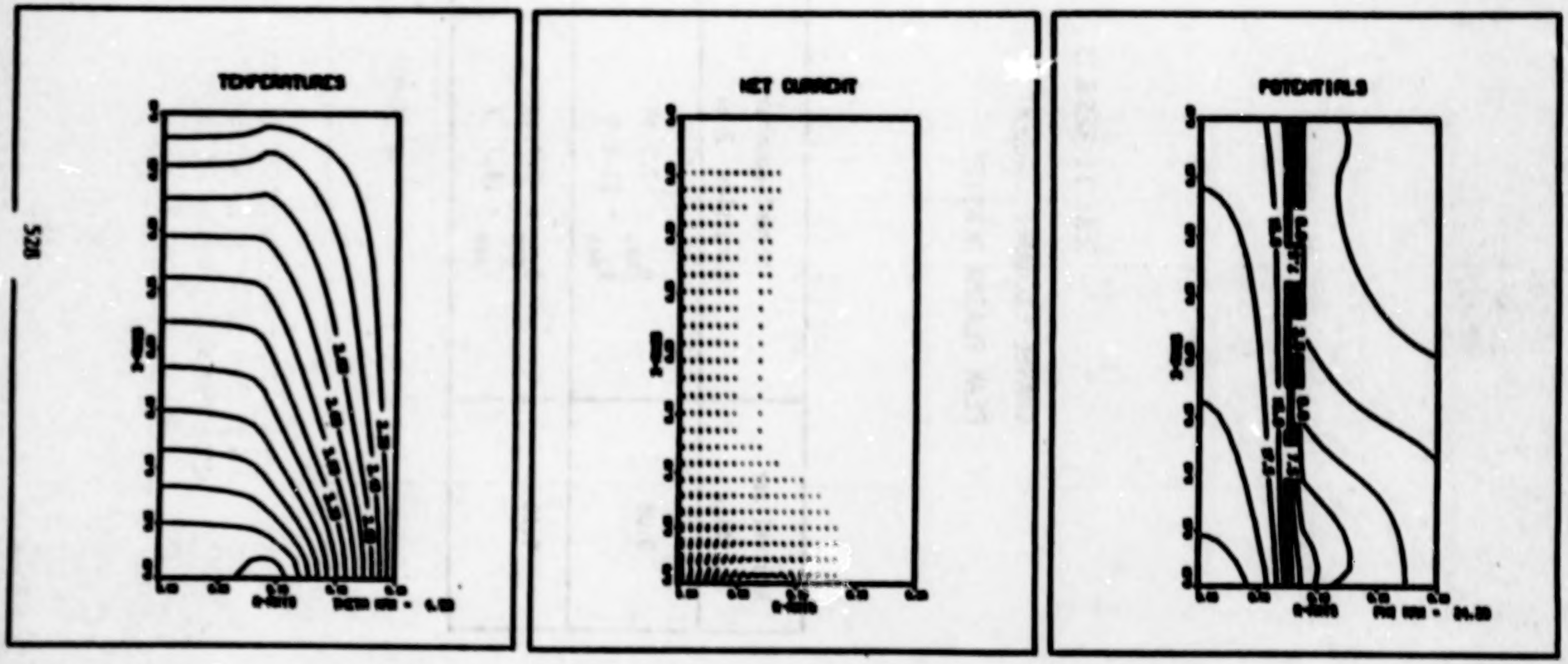
  -- Continuity, momentum, and energy equations

- $\nu_{eff} \simeq f_p$ from electron 2-stream instability

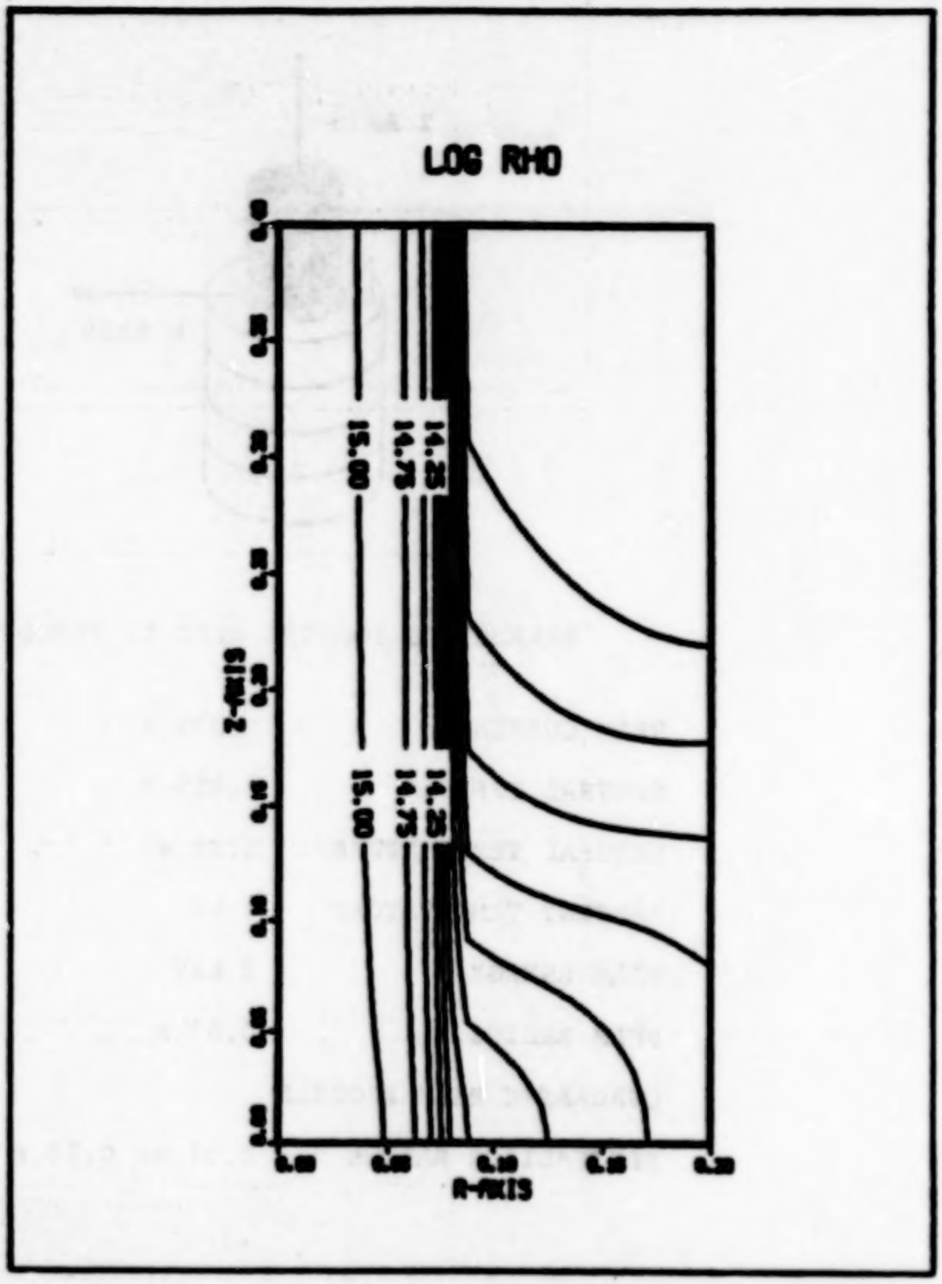
SERT II RESULTS

CHARGE EXCHANGE CURRENT	0.9 mA
PEAK PLASMA DENSITY	2×10^{15} m^{-3}

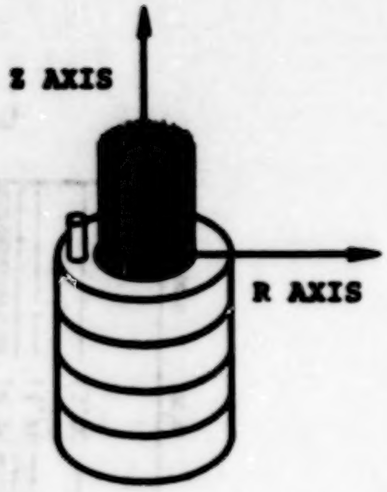
Neutralizer Position	Thermal Boundary Condition 2 eV	Insulating Thermal Boundary
0.08	θ_{max} = 2.3 eV ϕ_{max} = 13.8 V	θ_{max} = 4.1 eV ϕ_{max} = 21.3 V
0.10	θ_{max} = 2.4 eV ϕ_{max} = 14.7 V	θ_{max} = 4.5 eV ϕ_{max} = 24.2 V



Temperature, Current Density, and Potentials for SERT II Case: Insulating Orifice Plate; 10 cm Neutralizer Radius.



Logarithmic plasma density (beam plus charge exchange ions) for SERT II thruster cases. (Contour labels are common logarithm of density in m^{-3}.)



PARAMETERS FOR THE SERT II THRUSTER

BEAM CURRENT	0.085 A
NEUTRAL EFFLUX	0.055 A
NEUTRAL TEMPERATURE	0.06 eV
AMBIENT TEMPERATURE	2 eV
BEAM ENERGY	3 keV
BEAM RADIUS	0.07 m
QUADRATIC BEAM PROFILE	
NEUTRALIZER RADIUS	0.08 m; 0.10 m

ION BEAM NEUTRALIZATION CODE

- 2-D R-Z Geometry

- Finite element with fancy numerics

- Code requires as input
  - -- Ion currents
  - -- Ion densities
  - -- Boundary conditions on:

    Electron currents

    Electron temperatures

- Code predicts
  - -- Electron temperatures
  - -- Electron potentials
  - -- Net currents

CONSERVATION EQUATIONS FOR BULK PLASMA

- **Particle Conservation**

$$\left.\nabla \cdot N\vec{V} = 0 \right\} \text{ions}$$

$$\left.\begin{array}{l} \vec{\nabla} \cdot j = 0 \\ \vec{j} = ne(\vec{V} - \vec{V}_e) \end{array}\right\} \text{electrons plus ions}$$

- **Neutrality**

$$n = N$$

- **Electron Momentum**

$$\nabla p + en\vec{E} = \eta ne\vec{j}$$

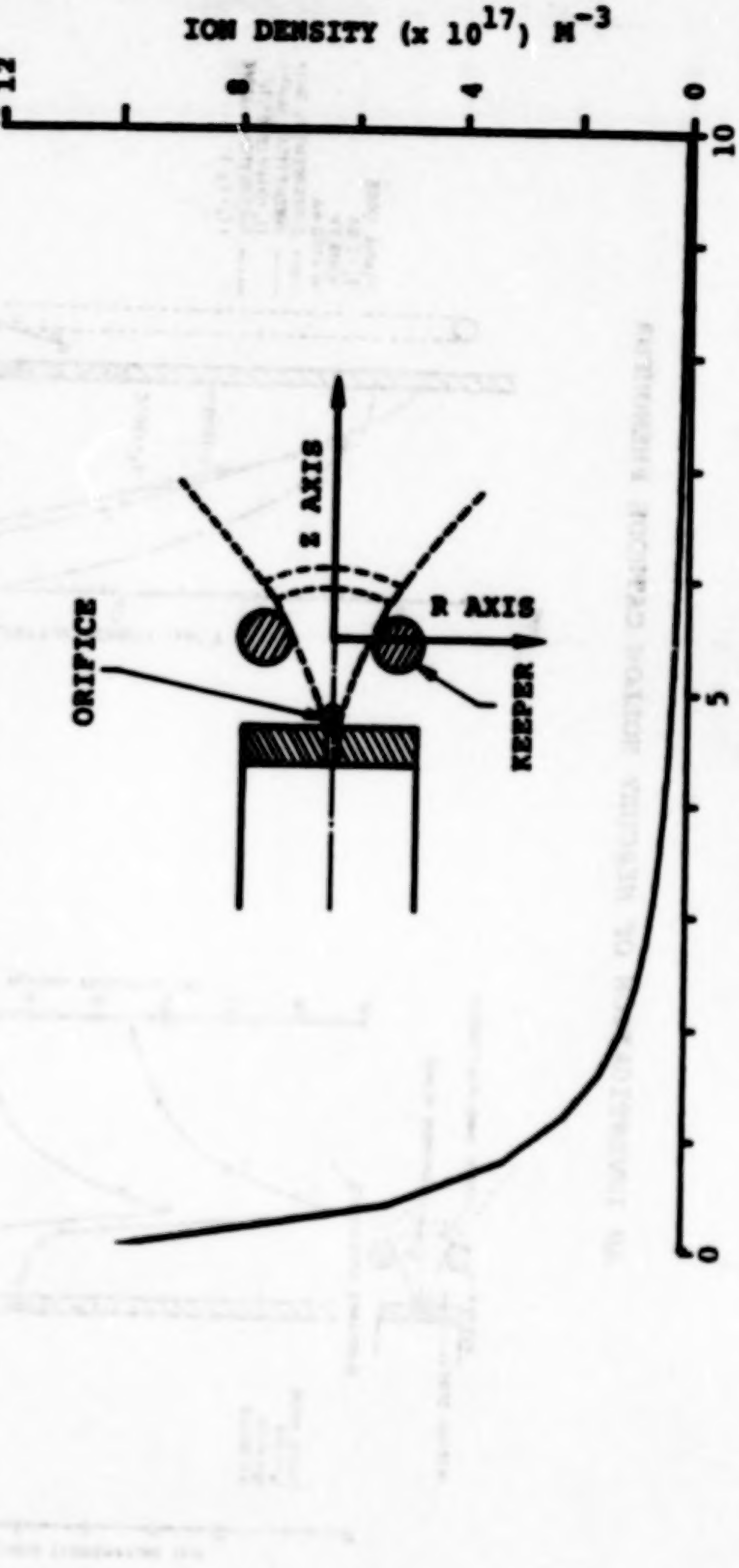
$$\eta^{-1} = \frac{\omega_p^2}{4\pi} \nu^{-1}$$

- **Electron Energy**

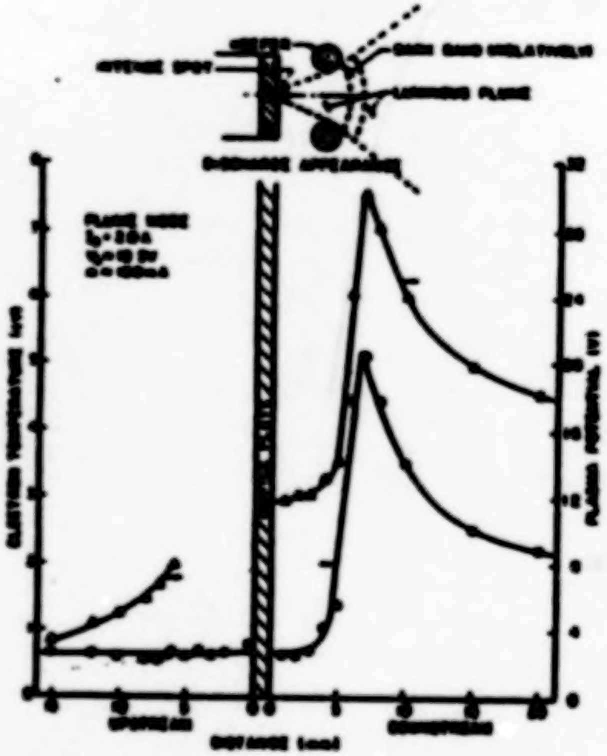
$$-\nabla \cdot \kappa \nabla \theta = \eta j^2$$

$$\kappa = \frac{3}{2} \eta^{-1} \left(\frac{k^2}{e} \right) \theta$$

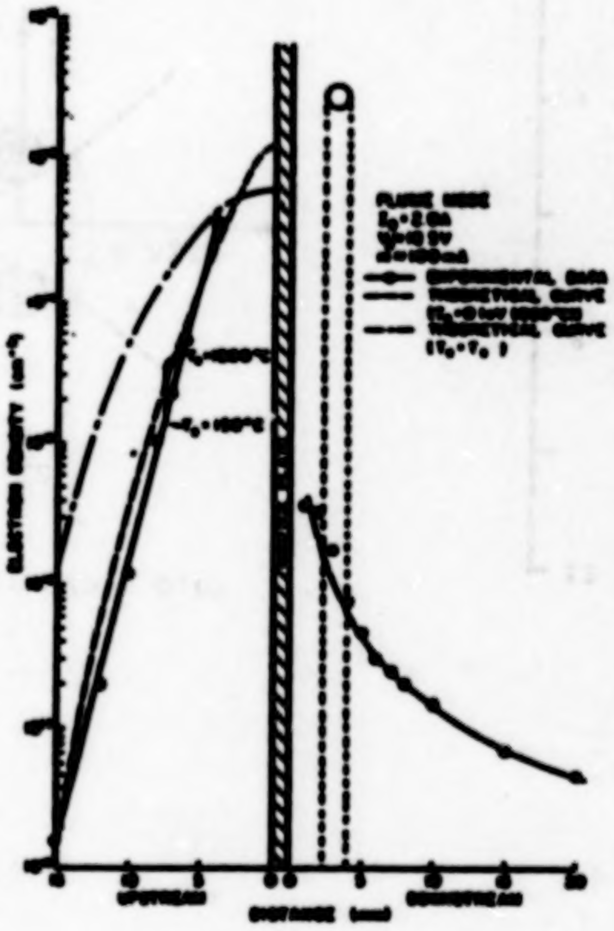
NEUTRALIZER DENSITIES (R = 0.0)



AN INVESTIGATION OF MERCURY HOLLOW CATHODE PHENOMENA



Cathode plasma potential and electron temperature profiles--plume mode.

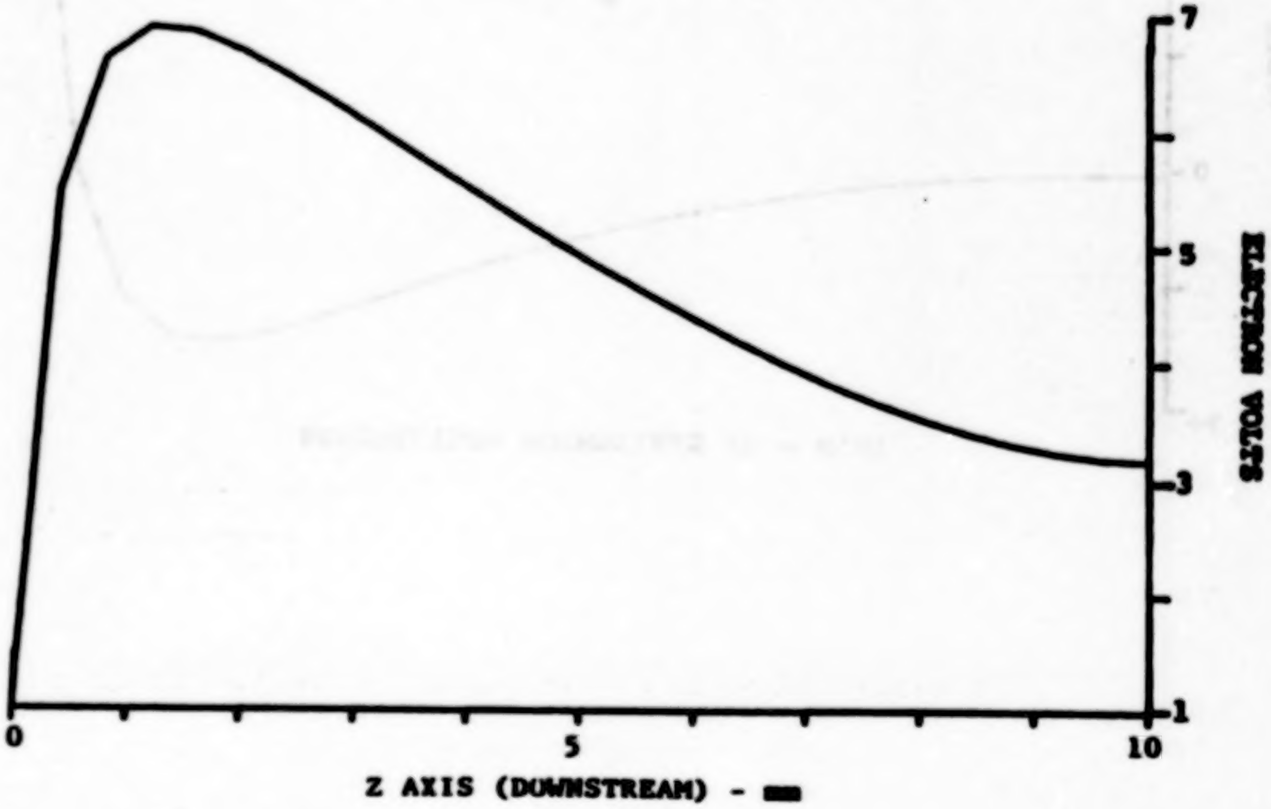


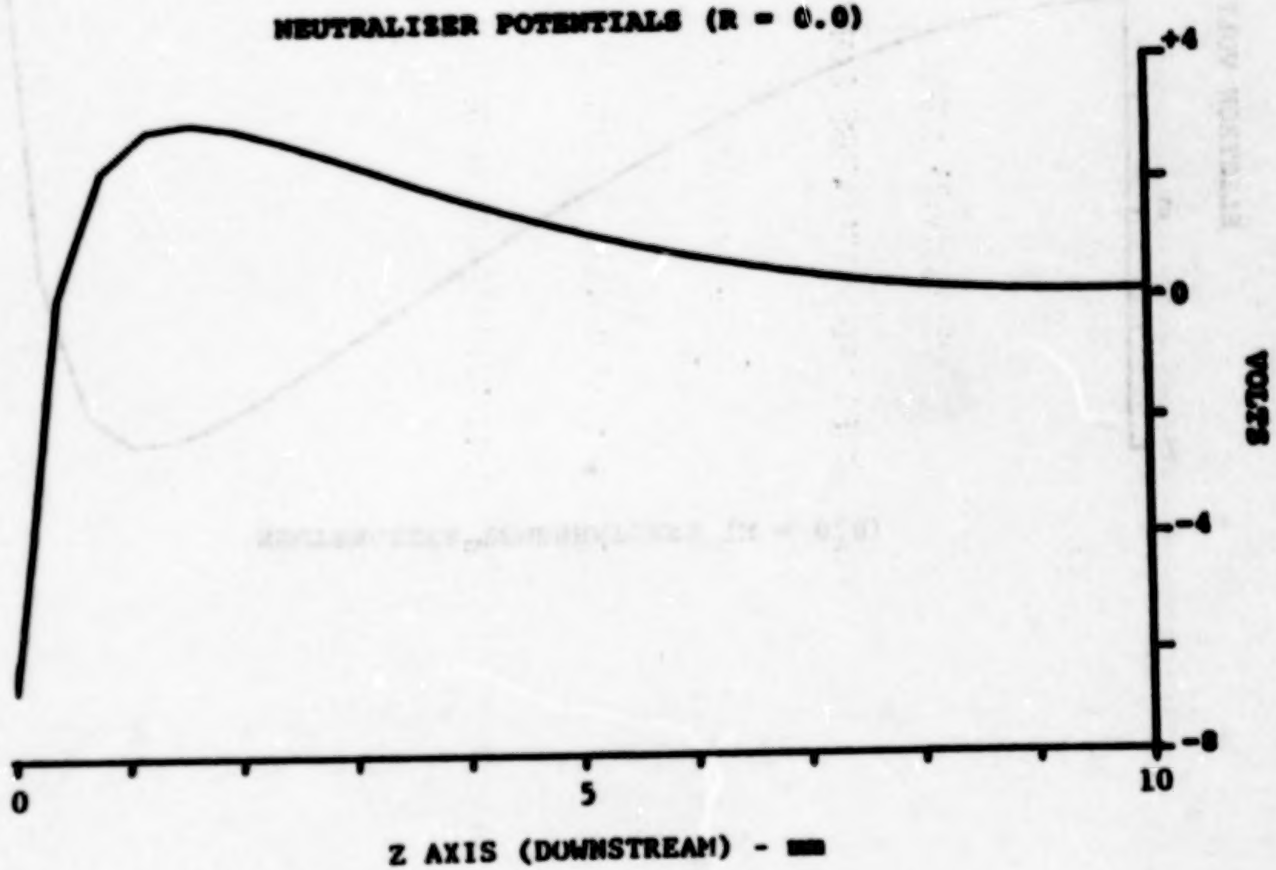
Cathode electron density profiles--plume mode.

ORIGINAL PAGE IS
OF POOR QUALITY

(D. E. Siegfried and P. J. Wilbur,
Colorado State University,
Fort Collins, CO)

NEUTRALISER TEMPERATURES (R = 0.0)





NEUTRALISER POTENTIALS (R = 0.0)

RESISTIVITY MODEL

- BASED UPON LITERATURE EXAMPLES
- $\nu \rightarrow \frac{\omega_P}{2\pi}$ when J/Jth ~ 1
- $\nu \rightarrow$ CLASSICAL J/Jth << 1
- INTERMEDIATE ION ACOUSTIC

FORMULATION:

$$\sigma = \epsilon_0 \omega_p / (\nu/\omega_p)$$

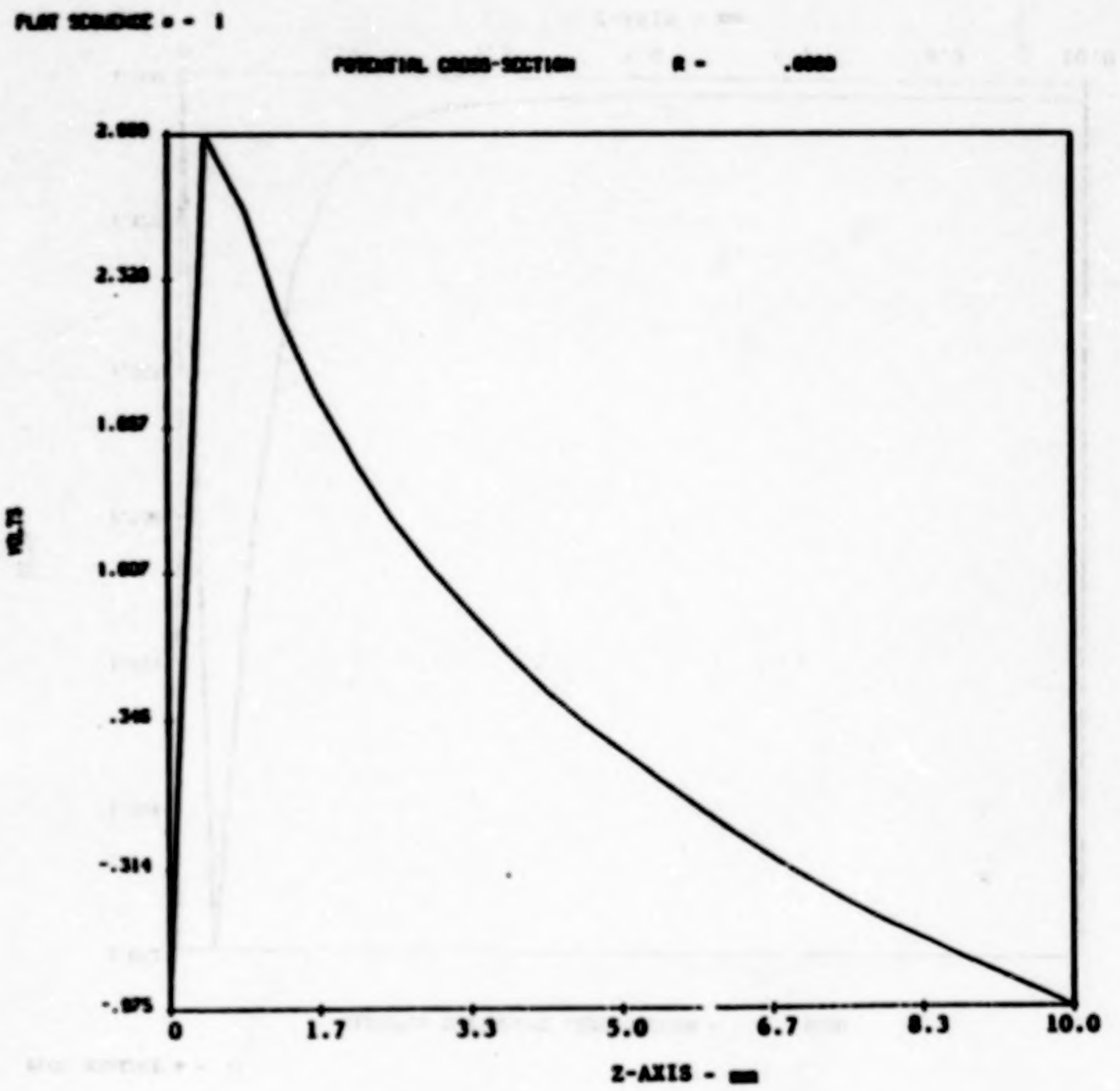
where

$$\begin{aligned}
\nu/\omega_p = {} & 10^{-13}\, n^{1/2}\, \lambda_c\, \theta^{-3/2} && \text{(Classical)} \\
& + \alpha_1\, e^{-\beta_1 J_{th}/J} && \text{(e - e)} \\
& + 2\alpha_2 (m_e/m_i)\, e^{-\beta_2 (n_e/J) \sqrt{e\theta/m_i}} && \text{(Ion-Acoustic)} \\
& + \frac{\alpha_3}{2\pi} \left(\frac{m_e}{m_i} \right)^{1/3} e^{-\beta_2 J_{th}/J} && \text{(Buneman)}
\end{aligned}$$

$\alpha_1 = 0.08;\ \beta_1 = 1$

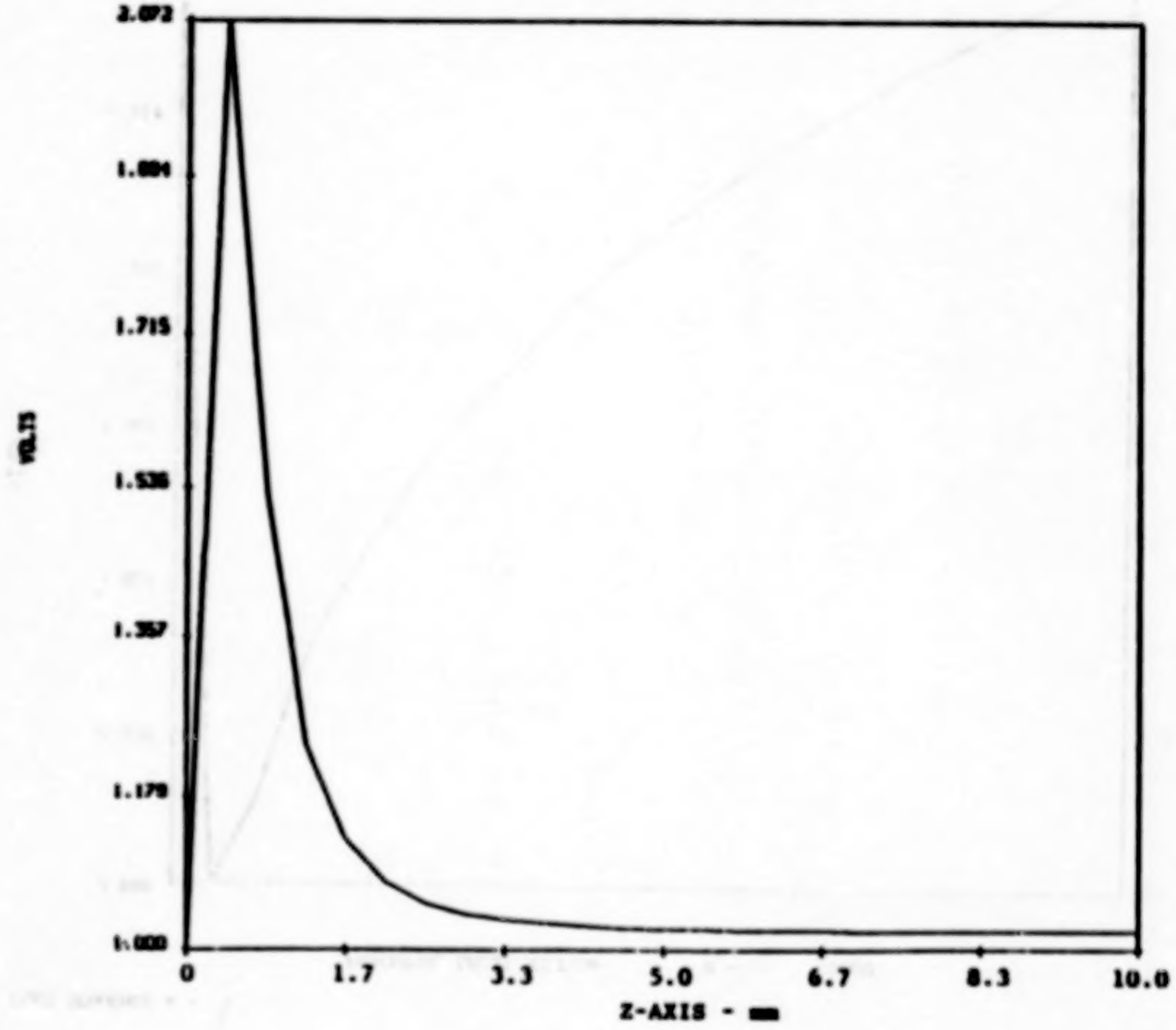
$\alpha_2 = \alpha_3 = 1$

$\beta_2 = \beta_3 = 1$


PLOT SEQUENCE # - 1
POTENTIAL CROSS-SECTION R - .0000
VOLTS
2.989
2.328
1.667
1.007
.346
-.314
-.975
0
1.7
3.3
5.0
6.7
8.3
10.0
Z-AXIS - mm

PLOT SEQUENCE # - 1

ELECTRON TEMPERATURE CROSS-SECTION - .0000



PLASMA SOURCE AS ELECTRON EMITTER

- LOCATED ON SHUTTLE
- FLUID MODEL OF ELECTRON TRANSPORT FROM ION THRUSTER NEUTRALIZATION STUDIES

  $\nu_e \simeq 0.1\,\omega_p$
- $Z_{eff} \simeq 20$ ohms

APPROXIMATION FOR PRESCRIBED DENSITY AND CONSTANT ELECTRON TEMPERATURE

$$n = \frac{n_o r_o^2}{r^2}$$

$$R = r_o \left[\frac{n_o}{n_{amb}} \right]^{1/2}$$

$$\theta \nabla n - ne \nabla \phi = \eta n e \frac{I}{4\pi r^2}$$

$$- \frac{\theta}{e} \ln \frac{n_o}{n_{amb}} + \phi(r_o) = \frac{I}{4\pi} \int_{r_o}^{R} \eta(r) \frac{dr}{r^2}$$

$$\phi_o(r_o) = \theta \ln \frac{n_o}{n_{amb}} + 9 \times 10^{11} \frac{\alpha I_{amp}}{r_o u_p(r_o)} \frac{1}{2} \ln \frac{n_o}{n_{amb}}$$

$$\alpha \simeq 0.1$$

PLASMA SOURCE AS ELECTRON COLLECTOR

- LOW ION GENERATION RATE,

  $$I_p < \sqrt{\frac{m_e}{m_i}}\; I_e$$

  - BIPOLAR SPACE CHARGE SHEATH
  - INCREASES I_e BY ~ 2
- MODERATE ION GENERATION RATE,

  $$\sqrt{\frac{m_e}{m_i}}\; I_e < I_p < I_e$$

  - QUASINEUTRAL WITH ELECTRON TRANSPORT
  - FLUID MODEL PREDICTS 10-1000Ω IMPEDANCE
- HIGH ION GENERATION RATE,

  $$I_p > I_e$$

  - QUASINEUTRAL WITH ION TRANSPORT
  - $\dot{m} \simeq A$ GRAMS/DAY AMPERE

PLASMA SOURCE AS ELECTRON COLLECTOR

- LOCATED ON SUBSATELLITE
- THREE MODES OF OPERATION DEPENDENT UPON PLASMA GENERATION RATE
- ALL WILL LOWER SHEATH IMPEDANCE

PLASMA SOURCE REQUIREMENTS FOR ELECTRON COLLECTION

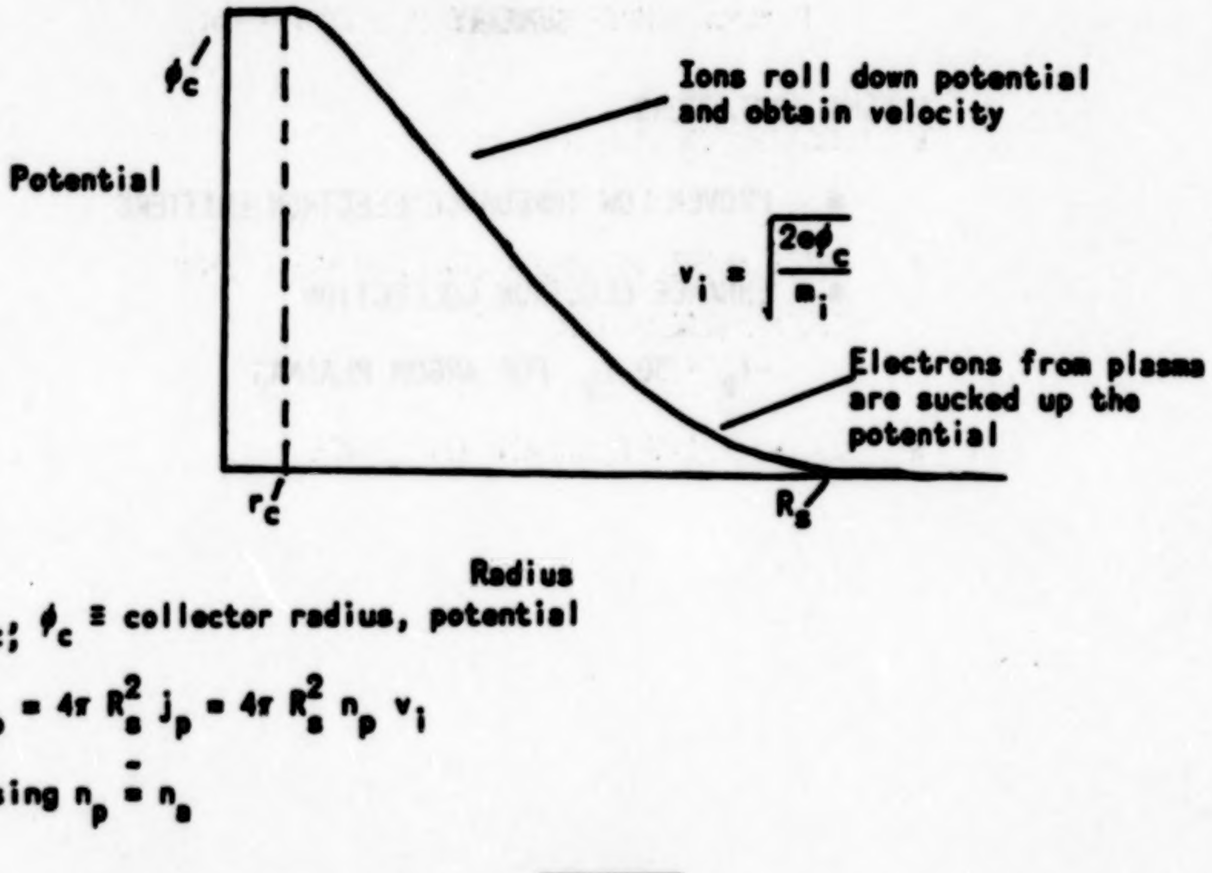
Given: $I_e \equiv$ electron current required

$\theta \equiv$ ambient plasma density and temperature

Theory States: $n_p = n_a$ on effective sheath, R_s, surface to maintain low potentials

For Spherical Collection:

$$I_e = 4\pi R_s^2 j_a = 4\pi R_s^2 n_a v_e$$



ϕ_c
Potential
Ions roll down potential and obtain velocity
$v_i = \sqrt{\frac{2e\phi_c}{m_i}}$
Electrons from plasma are sucked up the potential
r_c
R_s
Radius

r_c; $\phi_c \equiv$ collector radius, potential

$$I_p = 4\pi R_s^2 j_p = 4\pi R_s^2 n_p v_i$$

Using $n_p \cong n_a$

$$\cong 4\pi R_s^2 n_a v_i = I_e \frac{v_i}{v_e} = I_e \sqrt{\frac{m_e}{m_i} \cdot \frac{\phi_c}{\theta_e}}$$

$$I_p \cong I_e/30 \text{ for } \phi_c \sim 10 \text{ V}, \theta_e \sim 0.1 \text{ eV}, \sqrt{\frac{m_i}{m_e}} \sim 300$$

SUMMARY

PLASMA CONTACTORS

- PROVEN LOW IMPEDANCE ELECTRON EMITTERS
- ENHANCE ELECTRON COLLECTION

  $-I_e \sim 30\ I_p$ FOR ARGON PLASMAS

N86-28431

ELECTRODYNAMICS PANEL PRESENTATION

James McCoy
NASA/JSC

N86-28431

Electrodynamic Panel Presentation - James E. McCoy
NASA-JSC
October 16, 1985

PLASMA MOTOR GENERATOR (PMG)

I. General Description -

The first two charts are typical of several being used recently to describe applications growing out of studies the last 2-3 years at NASA, which have focused around the PMG concept employing plasma producing devices at each end of the tether to allow conduction of very high currents to/from the ionosphere.

Fig. 1 - Use of the tether system as a motor/generator for day-night power storage in a solar array based power system designed to provide 100 KW continuous power. The tether also provides the capability for orbit reboost/maintenance and a limited degree of orbital maneuvering.

Fig. 2 - An expansion on the orbit reboost and "deep discharge" capability ideas from fig. 1. A 200,000 kg spacecraft in LEO can generate 250 KWHR of electrical power at the expense of 1 km altitude loss, down to some minimum safe altitude. Conversely, 250 KWHR (plus or minus efficiency factors) of electrical power can reboost the orbit by 1 km. Therefore the trade-off between 3 months at 10KW and/or 9,000 lbs of hydrazine propellent. Note that the 3 months at 10KW could be obtained at the expense of a 90 km altitude loss, instead of 9,000 kg of hydrazine.

The next five charts describe the PMG tether systems being used to calculate the estimated performance data for use in these studies, as well as design reference for engineering or theoretical analysis. The workhorse system is called the 200 KW PMG. It is sized to suit the space station power levels and is generally suitable for most other utility applications. Other systems have also been defined for 2KW, 20KW, megawatt, and multi-megawatt application. These are essentially identical to the "200KW Reference System" except for scaling up or down in wire mass and hollow cathode (plasma contactor) capacity.

Fig. 3 - General description of the 200 KW PMG, including primary design features and trade-offs. The basic system uses no satelite at the far end(s), only a relatively small hollow cathode assembly. Special applications might add a ballast tether anchored at the end of the PMG cable (a sea anchor, or space anchor, type of function).

Fig. 4 - Descriptive summary of the "200 KW Reference System," showing major performance parameters at top, physical description and estimated mass of each component, summary of characteristics, and a breakdown of major loss terms to estimate each and show relative effect on overall efficiency figures derived at bottom line. Performance charts can be calculated by varying individual contributions according to operating current, engineering change, mass, or performance estimates, etc.

Fig. 5 - Same as fig. 4, values are for a higher capacity system operated at a lower, more "efficient" fraction of its peak capability.

Fig. 6 - Summary of most promising applications presently being studied, with some representative performance numbers.

Fig. 7 - Compares the PMG tether system with fuel cells and solar arays at various altitudes. The tether outperforms fuel cells any time the total power required is more than a few thousand KWHR; but for long term applications solar arrays always win in the long term - except at lower altitudes where their high drag makes them impractical,

unless tethers can be used to offset that drag.

II. Operating Principles -

The next set of charts displays the voltage drops and current contact geometries involved in operation of an electrodynamic tether, attempting to illustrate the comparative behavior of hollow cathodes, electron guns and passive collectors for current coupling into the ionosphere. The ionospheric conductivity itself is simply assumed large ($R \approx 1/2$ ohm) if the "plasma contractor" establishes electrical contact such that the return current is spread over a sufficiently large area.

Fig. 8 - The sketch at top shows the geometry of a 10 km tether wire operating between a spacecraft (left end) and a TSS size satellite (right end). Orbital velocity is directed into the paper and magnetic field perpendicular (up), so that induced voltage is directed toward the right (causing electron current flow in the wire from satellite toward spacecraft). Contact currents at each end will tend to be confined to "flux tubes" along the magnetic field as indicated, until cross-field diffusion can occur. This confinement might contain the currents along a flux tube until reaching the E-region where increased Cowling conductivity allows closure. Relative initial dimensions are shown, for thermal electrons, KeV electrons from a gun, or 1-10 eV ions from an argon plasma source. Other factors, such as formation of magnetodynamic waves/"Alfven Wings" may be important but are not illustrated. The entire disturbance is transient, moving across the "flux tubes" at orbital velocity. The middle figure shows the various voltage

drops thru the system, assumed operating with a low resistance wire and a resistive load (R_L) located near the spacecraft. Voltage drops occur at each end in the contact regions (sheath, electron gun, plasma cloud), which are characterized here as resistances (at R1 and R2) although they are in general very non-linear. The drop at the positive current end (R1) is often larger than the negative current (electron collecting, R2) end. The induced voltage (VXB·L = 2 KV, here) less the contact drops at both ends is the available working voltage to drive the total load R_L'. The wire resistance R_W is effectively in series with R_L as part of the total load ($R_L' = R_L + R_W$ $(+R_I)$), which also includes any signficant ionospheric impedance R_I, therefore reducing the effective working voltage at the load by $I(R_W + R_I)$. For motor operation, these terms all add to the required drive voltage. Finally, at the bottom is a summary of characteristic contact resistance, contact power loss, and contact area for each of the three contactor types.

Fig. 9 - Hollow Cathode Operation (Inner region): A cathode to anode/keeper discharge current (not shown) results in a high density core volume of weakly ionized, highly collisional plasma freely expanding into the surrounding vacuum (while its center of mass moves away from the HC orifice at sonic-choked flow exit velocity U). At large distances this becomes an expanding spherical cloud of low density, collisionless plasma. We model this as spherical expansion from a uniform "source region" of radius R_0 inside of which collisional (gas) dynamics maintain equilibrium, through a transition region of complex dynamics, to a series of expanding spherical shells of low density collisionless plasma extending to some distant radius where

they either merge with the ionosphere or become distorted by outside forces (magnetic field, etc.). Conservation of particles, plus estimates that $\dot{R}$ stays in the range of sonic to "Bohm" velocities yields an estimated total current conduction capacity of 10- 1,000 amperes. This might be increased if electron heating or sheath ionization occurs. To first order, the current can flow in either direction, from inner to outer boundary as frequently observed, or from outer to inner if the outer boundary is a source of electrons (probably true for a surrounding plasma, harder to simulate inside a laboratory chamber). The "ion current" required from the hollow cathode source is established by the loss rate from the "plasma ball" ($\dot{R} \times n \times R^2$), independent of actual tether current being drawn thru the system.

Fig. 10 - Hollow Cathode Operation (Outer Region): The expanding plasma cloud, radial velocity now assumed constant, falls off in density as R^{-2} until it is less than (lost in) the surrounding ionosphere. With no tether current through it, it will assume some equilibrium voltage distribution such that thermal current densities balance against the density gradient/thermal current gradient effects. This probably requires $\Delta\phi$ of a few times kT for every two orders of magnitude Δn. This is an equilibrium, with no net current flow. Any attempt to upset this equilibrium by putting either positive or negative voltage on the (hollow cathode source) end of the tether will result in exponential increases in current flow to oppose it, up to the limit where the tether current begins to dominate the thermal current densities/equilibrium conditions. Using the inner

boundary condition of $N_o = 10^{12}$/cc at $R_o = 10$ cm, this limit would be well in excess of 100 amperes at voltage drops less than 10 volts. If the magnetic field acts to impede these currents, the Bohm Diffusion equation would indicate that either electron heating or additional ionization of the neutrals would be required to allow conduction, and either condition could be satisfied by several mechanisms at relatively small additional voltage drop. Also, if magnetic connection occurs it will sweep away the plasma at orbital velocity, resulting in a higher source current required to sustain the plasma cloud. This will be delayed in practice by ExB drifts in the charge separation field set up in the finite width of plasma, which will tend to cause the plasma to continue moving with the source. The effective boundary of the plasma cloud can be defined at R = 100 m for a 10^6/cc surrounding ionosphere, expanding to R = 1km for a 10^4/cc ionosphere. Beyond this radius the ambient thermal current densities exceed those of the hollow cathode cloud and conduction becomes that of the ionosphere, rather than that of the hollow cathode. The plasmas adjust to each other, no changes in tether operation (accelerating voltage, discharge current, etc.) are needed.

Fig. 12 - Reference curve used in design studies to estimate hollow cathode power required versus maximum tether operation current (power for heaters, discharge current and extraction voltage). Verification of this curve by experiment data on orbit is a critical issue for present and future applications studies.

Power used = 100 + 50I (watts)

Fig. 13 - Plot of tether operating current versus power consumed in

operation, using PMG concept with hollow cathodes compared with existing electron guns (based on pervience of existing SEPAC and proposed TSS core equipment guns, extrapolated beyond 1 amp maximum planned operation).

Fig. 14 - A more general treatment of tether current contactor performance than fig. 13, plotting voltage drop across contact sheath/beam at each end of tether vs. tether current (to get power loss, multiply by I and add heater and controler power). The PMG hollow cathode design curve (from fig. 12 and fig. 13) is straight solid line at 25V. Actual data values measured in lab fall roughly along dashed line below that (see fig. 30). The fig. 13 curves for SEPAC and TSS guns are in upper left corner. Curves for other devices and/or other assumptions fall everywhere in between:

1) TSS satellite, space charge limited electron collection at 10^6/cc

◎ = no magnetic field ● = Parker & Murphy model

2) 30cm Kaufman thruster with electron beam (-I, only)

3) 30cm Kaufman thruster with ion beam (+I, only)

4) S-cubed model for hollow cathode, using NASCAP

5) PMG model, with electron heating/Bohm Diffusion @ (a)10^4/cc, (b) 10^6/cc

6) PMG model, with Parker and Murphy diffusion model @ (a)10^4/cc, (b) 10^6/cc

Fig. 15 - Insulation requirements and drag area in lower orbits strongly force moderate power (20KW-200KW) tethers toward maximum lengths of 10-20 km, if normal insulation thickness standards (100 volts/mil) are applied. Use of very highly stressed (5KV/mil) insulation could avoid part of this, but probably has severe problems with

pinhole leakage/breakdown phenomena at high voltage in a plasma environment.

Fig. 16 - Nature is hostile toward long, thin tethers. Electrically, 100 km of #12 wire weighs 900 kg and performs as efficiently as 10 km of #2 wire, which also weighs 900 kg. However, the 100 km wire (2 mm dia) can expect to be cut 15-20 times per year by meteoroids or debris, while the 10 km wire (6.5 mm dia) can expect 4-8 years between penetrating impacts. At this size, debris particles are the primary hazard. The debris problem is reduced at lower altitudes due to reduced dwell times in denser atmosphere. The Megawatt PMG Reference System (20km x 2cm dia) could expect 30 years between penetrations, in a 400 km orbit.

III. Massive Tether Dynamics

The basic PMG design involves a massive tether cable (or pair of cables deployed one up and one down) with little or no satellite mass at the far end(s). Deployment is permanent for most applications, therefore control law reeling for rapid deployment/retrieval is unnecessary. The IXB forces are dominant, leading to use of IXB time phasing, rather than tether reeling, for control. Special applications may benefit from use of secondary "ballast" tethers attached (in place of satellites) at the PMG far ends, but normally any weight that could be added to end mass to increase PMG tether tension/stability is more beneficial if distributed along the wire as a heavier conductor, thereby increasing electrical efficiency.

The dynamic behavior of the massive PMG tethers is distinctly different from the TSS configuration.

Fig. 17 - Summary of dominant factors in massive tether dynamics for PMG applications.

Fig. 18 - Illustration of massive tether (no satellite) under strong IXB (thrust) force disturbance; superimposed on simple massless tether model often used for discussions of tether fundamentals. Note the curvature of tether cable, location of center of gravity (c.g.) displaced from host spacecraft, relation between tether tension/deflection angle at c.g. and net acceleration force transmitted to c.g./spacecraft ($T \sin\alpha = F$).

Fig. 19 - Derivation of equations providing analytic approximation to two dimensional motion of massive tether. $T(z)$ is tension in tether and α is deflection from vertical (first solution is for $T(z)$ and $\sin\alpha$ if tether is at equilibrium), X_{tt} is acceleration at non-equilibrium point.

Fig. 20 - General solution requires computer modeling and has not yet been completely solved, but GTOSS provides useful approximation with wide applicability. Figure displays orbit, coordinates, and general configuration (model) used in following solutions for 100KW PMG, with optional "ballast" tether as shown and day/night cycle reversals of current to excite the critical out-of-plane libration resonant at half orbital period.

Fig. 21 - Results for 10,000 lb, 65,000 foot PMG system operating at 100 KW with 50/50 day-night power cycle (power storage/power generation, to replace battery system used with large solar array). This is the most critical situation for 2:1 resonance with the out-of-plane libration, and the libration is seen here to grow rapidly beyond 10 degrees by orbit #3, exceeding 30 degeres during orbit #5. Notice

the effect on tether voltage (EMF), which is seen to vary with magnetic field in the "normal" manner during orbit #3, between roughly 3,000 to 4,500 volts. By orbit #5, the tether is swinging so far away from the vertical that it becomes nearly parallel to the field at 30°N latitude and the EMF drops to only 400 volts! At this point the tether has become essentially useless, as well as nearly out of control. Such operation must be avoided.

Fig. 22 - Proposed simple method to avoid problem in fig. 21, other than by suspending or reducing day/night operations. This is also useful for the unrelated, but equally troublesome problem of variable angular rates in eccentric orbits - such as would occur during electrodynamic boost of a transfer orbit's apogee during perigee passes through low altitude. (A tether reel controller could be placed at either end of the "ballast" tether to further strengthen the control capabilities, in place of the ballast mass or where electric power is most easily provided by the PMG. The following calculations indicate this is not necessary. For any given mission, trade-offs between total mass and complexity/reliability of operation should be studied.)

Fig. 23 - Comparison between rate of increase in out-of-plane librations between (a) worst case (50/50 power cycle), (b) real world day/night power storage/generation (65/35 power cycle, thrust at 53KW during day, power generation at 100 KW during night) with "bare" PMG, and (c) same as (b) except stabliized by 1,000 lb passive ballast tether (no reeling). No attempt to reduce libration by selective phasing of IXB loading was made in these runs (i.e., "worst case" assumption, that power load could not be

adjusted at all to allow use of "electrodynamic control law"). The problem is substantially reduced in case (b), but definitely still present. In case (c), resonance appears to be broken, problem solved (long term runs would be needed to verify that secondary resonance terms don't eventually show up, but only if long term power budget stayed "locked in" to resonance condition). Therefore, no need for complex tether reeling mechanism is seen for this extreme case.

Fig. 24 - Corresponding in-plane libration (which is necessary factor in production of power or thrust via electrodynamic tethers on a single host spacecraft) for the three cases in fig. 23. Libration appears well behaved in all three cases.

Fig. 25 - Relative libration behavior of massive PMG cable end and ballast mass, showing relative phase shifts producing damping effect and disruption of phase resonance conditions.

IV. Jupiter Mission

In 16 years it will be 2001, and some time ago many of us were given a vivid impression that this might be the year man goes to Jupiter. Maybe the movie will not prove exactly accurate about the date, purpose, spacecraft, and crew; but Jupiter does provide a very good focus for considering the possible uses of electrodynamic tethers outside the "mundane" near earth applications for power, propulsion and research discussed so far. Jupiter has a very strong magnetic field (4 Gauss near the surface) providing a very extensive magnetosphere (extending more than a million miles), ideal conditions for electrodynamic tethers. While electrodynamic effects become too small for practical use with existing tether materials within a few thousand kilometers of the earth, they remain strong well beyond 300,000 km at Jupiter. The Jupiter magnetoplasma may be rather low density, but the hollow cathode plasma cloud can probably expand to adjust for this. In any case Jupiter provides a good example to examine some additional capabilities of the PMG tether, and is the most likely place outside low earth orbit to benefit from, or require the use of, electrodynamic tethers for its future exploration and development.

Fig. 26 - Plot of orbit energy within the Jupiter system, as shown yesterday during my general presentation to the opening session. The intense gravity makes it extremely difficult to get around within the inner system by use of rockets, either chemical or electric, for orbit transfer delta-V. The energy required to achieve Low Jupiter Orbit (LJO) is much more than required to get to Jupiter from the Earth. Expressed as millions of joules per kilogram (Mj/kg) or kilowatt hours per kg (KWHR/kg) it becomes clear that these energy levels are not practical for rocket propulsion, but well within the theoretical capabilities of electrodynamic tether propulsion. Also plotted (in green) is the velocity for circular orbit and (dashed green) corotational velocity of the magnetoplasma. The vertical scale reads in km/sec for the velocity plots. A very significant difference from the Earth's situation is that corotation becomes important, even dominant, relatively close to the planet at 2 R_J (about 70,000 km above the surface) where electrodynamic tether forces are still very strong. (At geosynchronous orbit, GEO, the magnetic field is too weak to be useful without a superconducting tether.)

Fig. 27 - The induced voltage for a radially aligned tether in circular orbit

versus distance is shown, under two different assumptions. The solid blue line ignores corotation (assumes the velocity in VXB is orbital velocity, and the velocity of the Jupiter "ionosphere" in return circuit is zero). The green line assumes 100% corotation. As a result, VXB goes thru zero, becoming negative (dashed green line) beyond 2.2 Jupiter radii. This is a fundamental difference. In this region, tether power generation no longer produces drag that decelerates the spacecraft toward lower orbits, but instead produces thrust that accelerates it toward higher orbit. Near 2.2 R_J, the VXB induced voltage in the tether is rather low, while the IXB thrust force is still large. At exactly the corotation radius, the power required to drive a current against the tether EMF is zero while the thrust (per ampere) is still greater than that available in LEO at a cost of 8KW/newton! This is not a paradox, or a perpetual motion machine. It is a simple result of the fact that the electrodynamic tether couples to the frame of motion of the magnetoplasma surrounding it. If the rest frame of that magnetoplasma is not the same as the gravitational rest frame of its orbit, energy is naturally transferred. Beyond 2.2 Jovian radii in a corotating magnetosphere, IXB drag does just that, it drags the tether along toward the corotational velocity as long as the magnetosphere remains firmly coupled to the rotation of the planet, or toward whatever intermediate velocity may be the effective rest frame of the magnetoplasma! The same phenomena should be seen in the solar wind (where V = 400 km/sec is very high compared to orbit velocity around the sun, and orbital velocity is a negligible term for an "Alfven Engine") or in LEO (where corotation is about .5 km/sec, much less than orbit velocity - would produce a small, but noticable difference between posigrade and retrograde equatorial orbits). If the condition of corotation is satisfied, the Jupiter Synchronous Orbit (JSO) is a unique point in the solar system. A space station (space factory, or space city) located at JSO would be anchored stationary with respect to the Jupiter magnetosphere. By deploying a pair of tethers, one up into higher velocity magnetoplasma and one down into lower velocity magnetoplasma, both tethers could be used to produce power while providing balanced (off-setting) drag/thrust forces on the space station. This particular space station could then consume all the tether generated power it wanted and never have to reboost (or relower, in the case of solar orbiting "Alfven Engines" or spacecraft higher than JSO) its orbit. Somewhat analogous to how a hydroelectric plant gets "free" power as long as rain keeps falling uphill from its location, the Jupiter corotating station can get "free" power from the planet's rotational energy as long as the planet continues to drive a corotational magnetosphere.

Fig. 28 - Comparison of tether tension and thrust/drag force, for a gravity gradient stablized tether system in circular orbits around Jupiter. The low density of Jupiter causes the gravity gradient force to be relatively small, even for a very long PMG tether. This would limit operation to a small fraction of peak available power (the PMG aassumed for this graph would be capable of 2 Megawatts in LEO, 200 Megawatts in LJO), unless additional stabilizing force is provided. This is readily done. Jupiter based PMG's would either use a long "anchor" of low mass (see "ballast" tether in fig. 20,

22) to maintain gravity gradient alignment, or would use several short PMG's arranged in a spinning configuration for contrifugal force stabilization.

V. Demonstration Experiments

Obviously, the PMG electrodynamic tether is a very powerful device; if and only if the hollow cathode current coupling, as well as the ionospheric plasma return current conductance common to all electrodynamic tether concepts, works as it is assumed in these studies. Confirmation of this assumption, even to order of magnitude, is critical to the validity of all the important results discussed today. Flight of a hollow cathode experiment on TSS, as well as detailed scientific study of the TSS electrodynamic interactions, is vital.

It is also important to verify, as soon as possible, the current coupling performance of a hollow cathode system in LEO to confirm our present emphasis on PMG type tether designs, rather than passive balloon and/or electron gun based concepts. Laboratory tests have been performed that indicate the model is correct, at least for electron emission, but extrapolation of plasma chamber test data to space plasma conditions is uncertain.

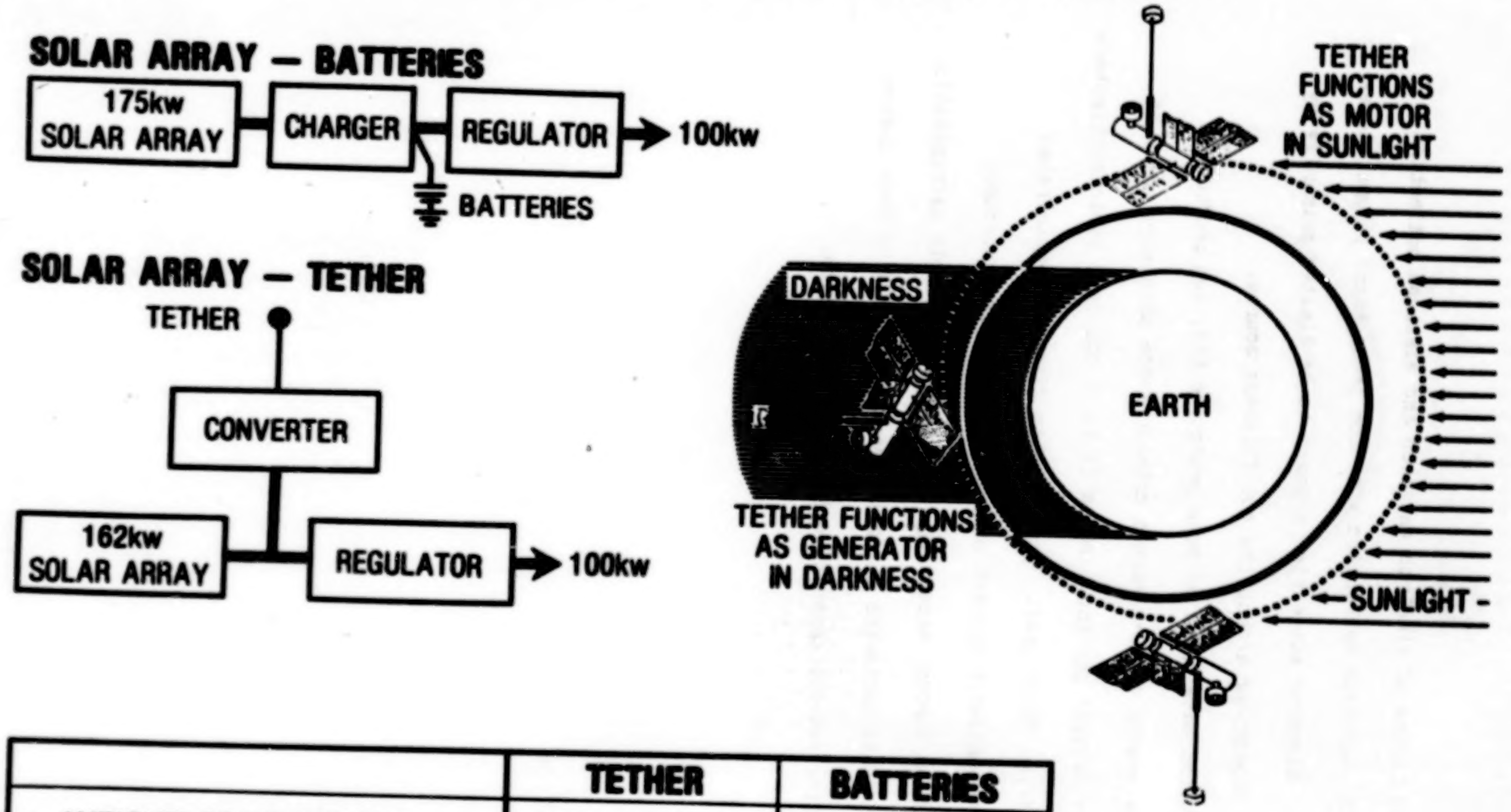
Fig. 29 - A small "experiment of opportunity" is being built at NASA-JSC, named PMG/POF (Plasma Motor-Generator/Proof of Function) Experiment. Scheduled for Space Shuttle flight on the Hitchhiker G carrier's second flight (HHG-2) in 1986, it is designed to measure the current/voltage characteristics of a pair of hollow cathode devices operating at 200 meter separation in low earth orbit.

Fig. 30 - Calibration data taken at Colorado State University, using a prototype hollow cathode assembly (HCA) built for PMG/POF.

Measured values of electron emission and electron collection currents (electron collection via "ion production" plasma, lower curve). Electron collection appears to be limited primarily by sheath impedances around the hot filament source.

Fig. 31 - Calibration data taken on same prototype HCA, ion production (plasma source volume) versus cathode/anode discharge power at various neutral gas input rates (1 to 18 standard cubic centimeters per minute, Xenon gas). Test results directly demonstrated electron emission current exceeding 1.5 amperes, electron collection current exceeding .15 ampere. Resonable extrapolation of this data indicates ultimate current capacity of this system exceeding several amperes, emission or collection.

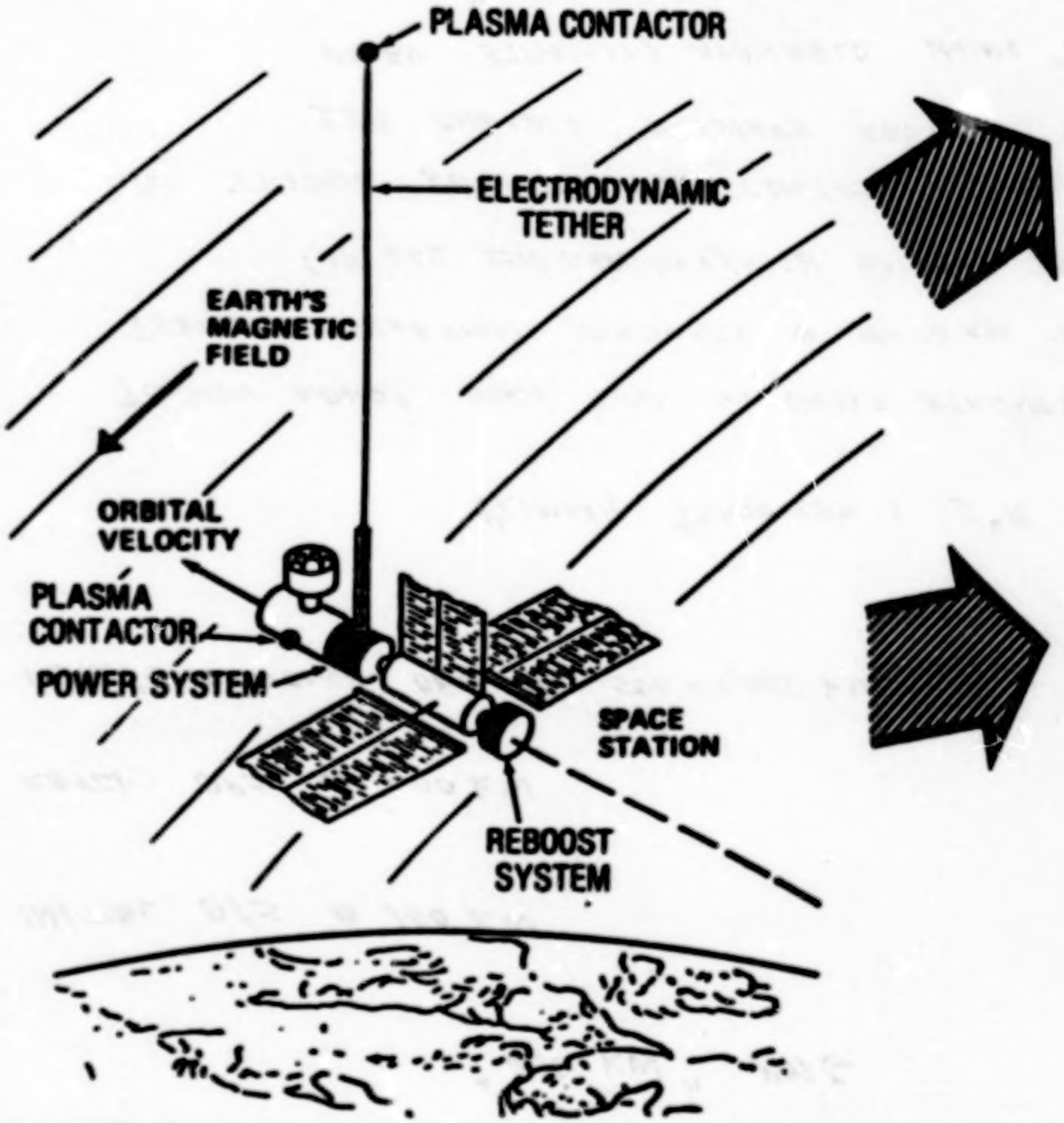
ELECTRODYNAMIC TETHER ENERGY STORAGE


SOLAR ARRAY — BATTERIES
175kw SOLAR ARRAY
CHARGER
REGULATOR
100kw
BATTERIES
SOLAR ARRAY — TETHER
TETHER
CONVERTER
162kw SOLAR ARRAY
REGULATOR
100kw
TETHER FUNCTIONS AS MOTOR IN SUNLIGHT
DARKNESS
EARTH
TETHER FUNCTIONS AS GENERATOR IN DARKNESS
SUNLIGHT

	TETHER	BATTERIES
• WEIGHT COMPARISON	15K LBS	24K LBS
• HEAT REJECTION REQMTS	40,000 BTU	75,000 BTU
• DEEP DISCHARGE CAPACITY	57,000 KWH	50 KWH

Figure 1

BACKUP TO SPACE STATION PRIME POWER AND REBOOST SYSTEMS


PLASMA CONTACTOR
ELECTRODYNAMIC TETHER
EARTH'S MAGNETIC FIELD
ORBITAL VELOCITY
PLASMA CONTACTOR
POWER SYSTEM
SPACE STATION
REBOOST SYSTEM

POWER SYSTEM FAILURE

- USE TETHER AS GENERATOR
- MAKEUP INCREASED DRAG WITH REBOOST MODULE
- 3 MONTHS AT 10kw FROM 9,000lbs HYDRAZINE

REBOOST MODULE FAILURE

- USE TETHER AS MOTOR FOR REBOOST
- USE POWER FROM SOLAR ARRAY SYSTEM
- SPACE STATION DRAG MAKEUP REQUIRES ONLY 5—8 kw OF SOLAR ARRAY POWER

Figure 2

"200 kW" PMG

INITIAL OPS @ 100 kW

RATED OPS @ 200 kW

PEAK/EMERGENCY OPS @ 500 - 1,000 kW

PRIMARY TRADE-OFF : I^2R POWER LOSSES vs TETHER MASS

TENSION LOADS VERY LOW vs CABLE STRENGTH (AL WIRE)

TEFLON INSULATION ADEQUATE @ 10-20 km TETHER LENGTH (2-4 kV)

(IF USE LOW CURRENT/HIGH VOLTAGE TETHER, INSULATION HEAVY & UNCERTAIN)

NO TETHER REELING FOR CONTROL

IXB PHASING PRIMARY CONTROL TECHNIQUE

ADDED STABILITY AVAILABLE USING "BALLAST" TETHER EXTENSION

"MASSLESS" KEVLAR TETHER w 10% END MASS

COULD STUDY "REEL CONTROLER" LOCATED @ FAR END

Figure 3

PMG - 200 KW REFERENCE SYSTEM

TETHER LENGTH	20 KM (10 UP+10 DN)	WORKING TENSION	42 N
NOMINAL VOLTAGE	4 KV	WORKING ANGLE	17 DEG
RATED POWER	200 KW	RATED THRUST	25 N
PEAK POWER	500 KW	PEAK THRUST	>100 N

CONDUCTOR	#00 AWG ALUMINUM WIRE DIAMETER 9.3 MM @ 20°C RESISTANCE 8.4 OHMS @ 20°C 7.7 OHMS @ 0°C 7.1 OHMS @-20°C	3640 KG
INSULATION	0.5 MM TEFLON (100 VOLTS/MIL)	278 KG
FAR END MASS	50 AMP HOLLOW CATHODE ASS'Y (INCLUDING ELECTRONICS & CONTROL)	25 KG
TETHER CONTROLLER	ELECTRONICS & MISC. HDWR. (POWER DISSIPATION LOSSES @1% = 2 KW)	94 KG
ARGON SUPPLY & CONTINGENCY RESERVE		163 KG
TOTAL		**4,200 KG**

TETHER DYNAMICS CONTROL	PASSIVE, IXB PHASING	
TETHER CURRENT/POWER CONTROL	DC IMPEDANCE MATCHING	
TETHER OUTSIDE DIAMETER	10.3 MM	
TETHER BALLISTIC DRAG AREA	206 SQ METERS	
DRAG FORCE @ 10^{-11} KG/M^3 (300 KM 1976 USSA-400 KM SOLAR MAX)	.12 N	.96 KW
I^2R LOSSES @ 200 KW		19.25 KW
HOLLOW CATHODE POWER		2.50 KW
IONOSPHERIC LOSS @ 50 AMP		1.25 KW
TOTAL PRIMARY LOSSES		23.96 KW
EFFICIENCY	ELECTRIC (177 KW NET @ 50 AMP/200 KW)	88.5%
	OVERALL (201 MECH. TO 177 ELEC. KW)	88.1%
INCLUDING CONTROLLER/POWER PROCESSER LOSSES @ 1%		2.00 KW
TOTAL (NET POWER OUT 175.0 KW)		25.96 KW
FINAL EFFICIENCY	ELECTRIC = 87.5%	OVERALL = 87.1%

Figure 4

PMG - MEGAWATT REFERENCE SYSTEM

TETHER LENGTH	20 KM (10 UP+10 DN)	WORKING TENSION	190 N
NOMINAL VOLTAGE	4 KV	WORKING ANGLE	10 DEG
RATED POWER	500 KW	RATED THRUST	65 N
PEAK POWER	>2 MW	PEAK THRUST	>400 N

CONDUCTOR	2 CM ALUMINUM WIRE DIAMETER 20.0 MM @ 20°C RESISTANCE 1.68 OHMS @ 20°C 1.54 OHMS @ 0°C 1.42 OHMS @-20°C	17,860 KG
INSULATION	0.5 MM TEFLON (100 VOLTS/MIL)	580 KG
FAR END MASS	125 AMP HOLLOW CATHODE ASS'Y (INCLUDING ELECTRONICS & CONTROL)	50 KG
TETHER CONTROLLER	ELECTRONICS & MISC. HDWR. (POWER DISSIPATION LOSSES @1% = 5 KW)	120 KG
ARGON SUPPLY & CONTINGENCY RESERVE		290 KG
TOTAL		19,000 KG

TETHER DYNAMICS CONTROL	PASSIVE, IXB PHASING	
TETHER CURRENT/POWER CONTROL	DC IMPEDANCE MATCHING	
TETHER OUTSIDE DIAMETER	21.0 MM	
TETHER BALLISTIC DRAG AREA	420 SQ METERS	
DRAG FORCE @ 10^{-11} KG/M^3 (300 KM 1976 USSA-400 KM SOLAR MAX)	.25 N	2.0 KW
I^2 R LOSSES @ 500 KW		24.1 KW
HOLLOW CATHODE POWER		5.0 KW
IONOSPHERIC LOSS @ 125 AMP		7.8 KW
TOTAL PRIMARY LOSSES		36.9 KW
EFFICIENCY	ELECTRIC (463.1 KW NET @ 500 KW) OVERALL (502 MECH. TO 463 ELEC. KW)	92.6% 92.3%
INCLUDING CONTROLLER/POWER PROCESSER LOSSES @ 1%		5.0 KW
TOTAL (NET POWER OUT 458.1 KW)		41.9 KW

FINAL EFFICIENCY ELECTRIC = 91.6% OVERALL = 91.3%

Figure 5

ELECTRODYNAMIC TETHER

RECOMMENDED APPLICATIONS

I. THRUST - USE WITH SOLAR ARRAYS IN LOW EARTH ORBIT TO OFFSET DRAG

- 100 KG SYSTEM PRODUCING .1 NEWTON THRUST
- 8 KW/N ELECTRIC POWER CONSUMPTION = .8KW
- ELIMINATES DELTA-V FUEL REQUIRED: >1,000 KG/YR
- KEEP 100 KW SOLAR ARRAY @ SPACE STATION ORBIT
  - INCREASE TO 200 KG SYSTEM @ 1-2 N THRUST
  - KEEP SPACE STATION + 100KW ARRAY IN <300 KM ORBIT ALTITUDE
  - NO ORBIT MAINT. FUEL REQUIRED; CONSUMABLES = < 60 KG/YR (ARGON)
  - USES 10-15 KW FROM 100 KW AVAILABLE

II. THRUST - USE FOR ORBITAL MANUEVERING PROPULSION

- 2,000 KG SYSTEM (PLUS 80 KW POWER SUPPLY: SOLAR, NUCLEAR, WHAT-EVER)
- 10 NEWTON THRUST - CONTINUOUS AS LONG AS POWER AVAILABLE
- ALTITUDE CHANGE
  - 7 KM/DAY - 200,000 KG (SPACE STATION)
  - 30 KM/DAY - 50,000 KG (PLATFORM)
  - 150 KM/DAY - 10,000 KG (FREE-FLYER)
- TOTAL IMPULSE: 864,000 N-SEC/DAY (194,000 LB-SEC/DAY)
  - 17 M/SEC/DAY - 50,000 KG (PLATFORM)
  - 86 M/SEC/DAY - 10,000 KG (FREE-FLYER, OMV, OR "TUG")
- ORBIT PLANE CHANGE: 30 DEGREE IN 6 MONTHS MAY BE POSSIBLE
- "FLY" ENTIRE SPACE STATION DOWN TO 200-250 KM ALTITUDE & MAINTAIN
- GROWTH VERSION: 200 N @ 1.6 MW, 20,000 KG + POWER SUPPLY

III. POWER STOREAGE - 100KW SOLAR ARRAY SYSTEM
+ 2,000 KG REVERSIBLE MOTOR/GENERATOR TETHER SYSTEM

- 60 KW THRUST DURING DAY (POWER STOREAGE AS ORBIT ENERGY)
- 100 KW POWER GENERATION DURING DARK
- TOTAL SYSTEM WEIGHT 40% OF CONVENTIONAL ARRAY WITH BATTERIES
- 10% REDUCTION IN SOLAR ARRAY SIZE
- 60% REDUCTION IN POWER PROCESSING HEAT REJECTION REQUIRED

Figure 6

CONSUMABLES REQUIRED VS ORBIT ALTITUDE

100kw NET POWER GENERATED

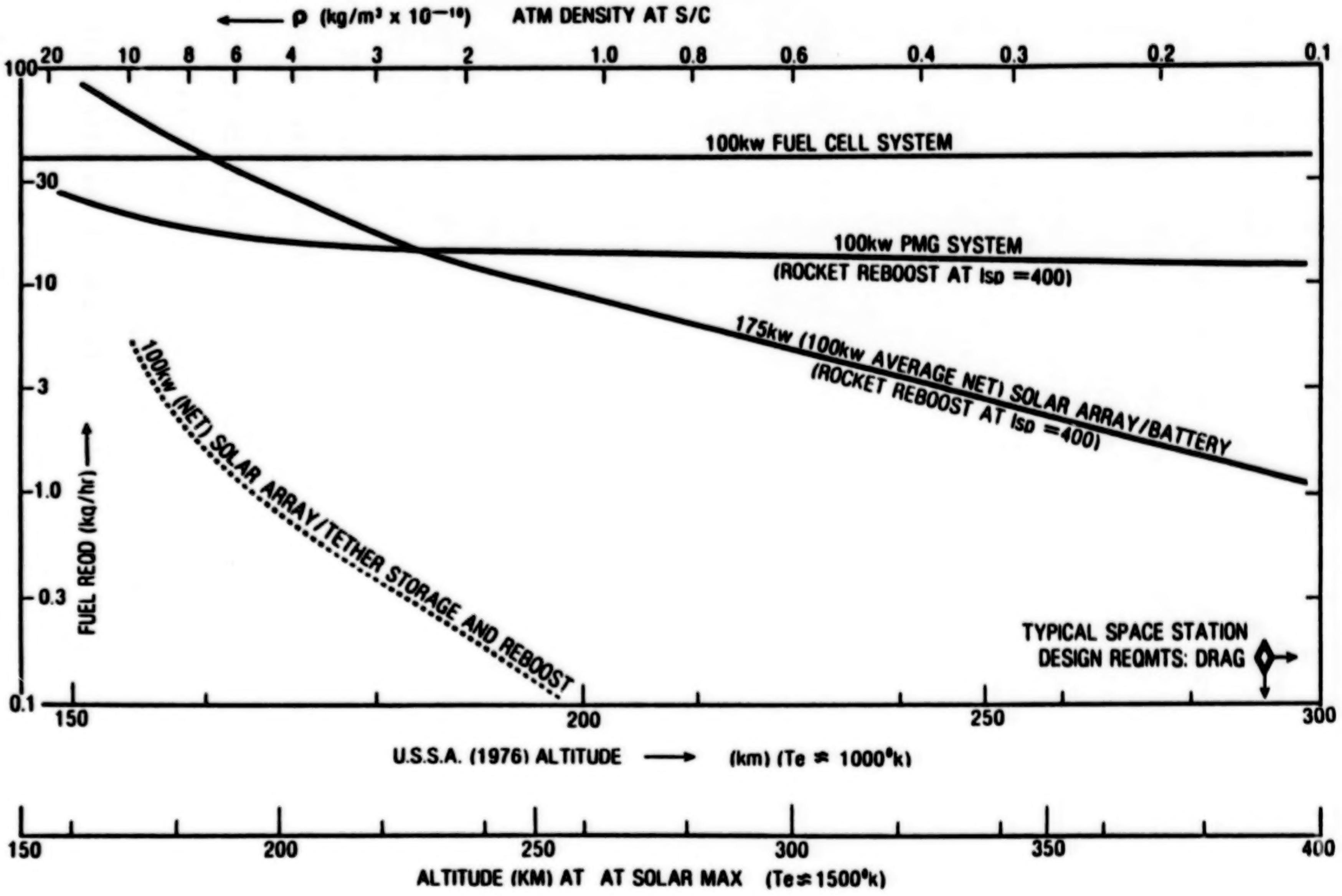
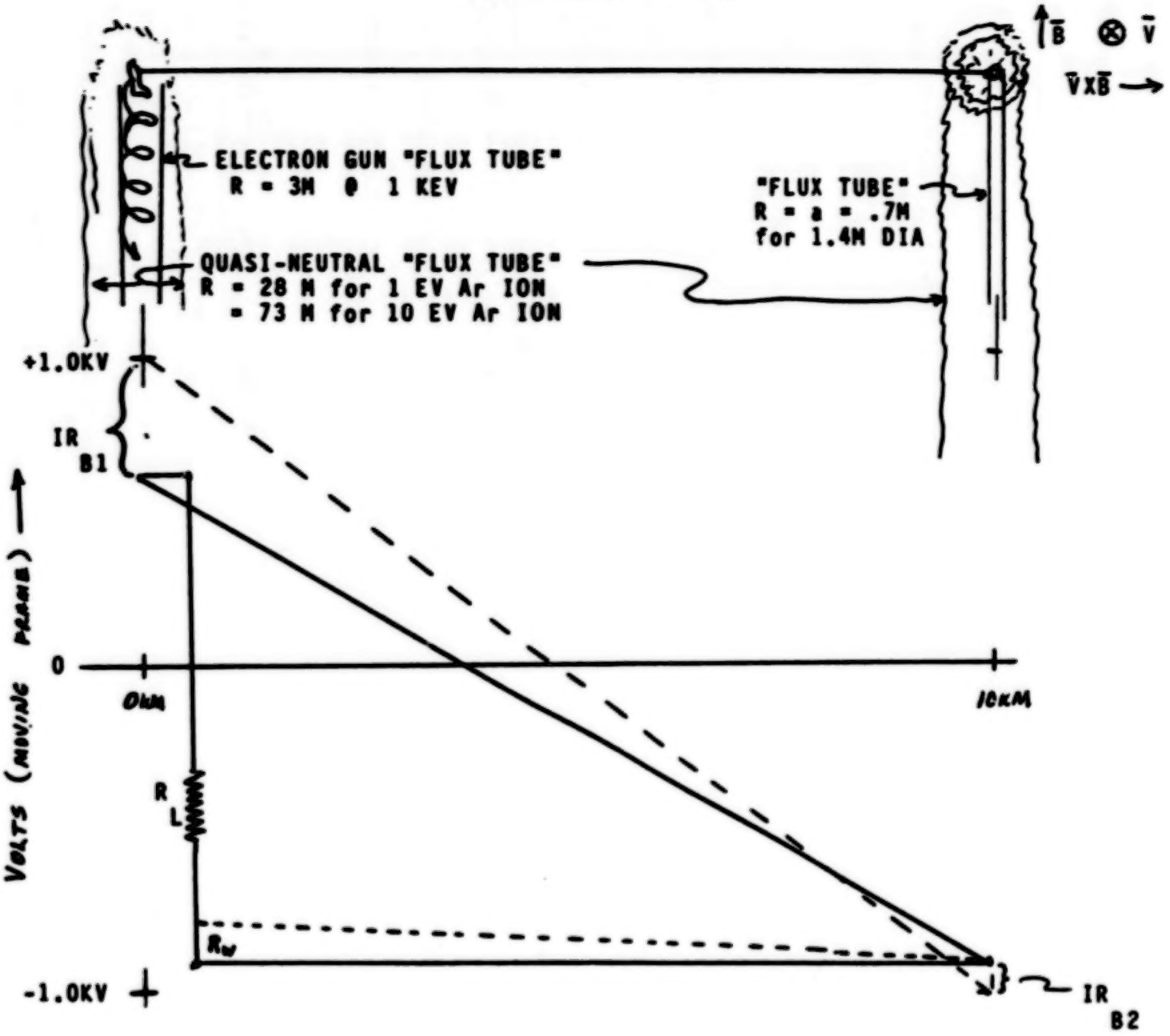


Figure 7

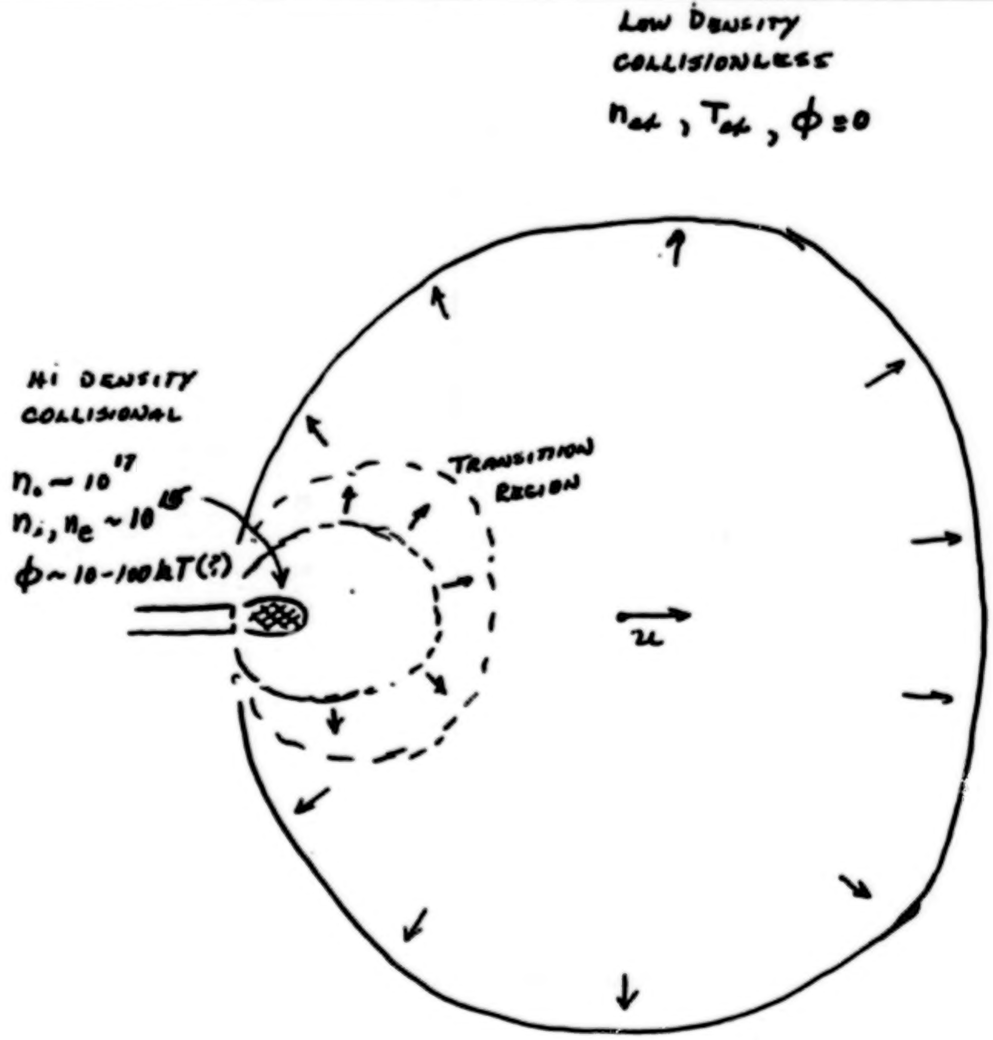
C-7

ELECTRODYNAMIC TETHER


$\uparrow \bar{B}$ $\otimes \bar{V}$
$\bar{V} \times \bar{B} \rightarrow$
ELECTRON GUN "FLUX TUBE"
R = 3M @ 1 KEV
"FLUX TUBE"
R = a = .7M
for 1.4M DIA
QUASI-NEUTRAL "FLUX TUBE"
R = 28 M for 1 EV Ar ION
= 73 M for 10 EV Ar ION
+1.0KV
IR_{B1}
VOLTS (MOVING FRAME)
0
0KM
10KM
R_L
R_W
-1.0KV
IR_{B2}

	PASSIVE COLLECTOR	ELECTRON GUN	HOLLOW CATHODE
R_{B1}	(SCL) SHEATH 0-1,000 for +I 0-100 for -I	PERVIENCE 100-1,000 for +I infinite for -I	QUASI-NEUTRAL < 1 for ±I (?)
PB1	0 watts (+DRAG)	.5 - 5 KW	100 - 300 watts
CONTACT AREA	$\frac{D^2}{4}$	20 M^2	>400 M^2 (?)

Figure 8


Low Density
COLLISIONLESS
$n_{\alpha t}$, $T_{\alpha t}$, $\phi = 0$
Hi DENSITY
COLLISIONAL
$n_o \sim 10^{17}$
$n_i, n_e \sim 10^{15}$
$\phi \sim 10\text{-}100\,kT(?)$
TRANSITION REGION
u

w/o B Field

EXPANDING SPHERE(S) w $u = V_o$

$$(\dot{R}_1)\, n_1 R_1^2 = n_2 R_2^2\, (\dot{R}_2)$$

@ EQUILIBRIUM $n_{io} \simeq 10^{14} \rightarrow n_{iex} \sim 10^{6}$

w $\nabla\phi \ni$ RETARD ELECTRONS

(ACCEL. IONS : "BOHM CONDITION")

$$V_i = \sqrt{\frac{kT_e}{m_i}}$$

@ ANY R, $j_e \sim ne\sqrt{\frac{kT_e}{m_e}}$

$\therefore$ CAN SUPPORT A CURRENT

$$I \sim 4\pi R^2 j_e = 4\pi \underset{\substack{\uparrow \\ \text{const.}}}{(R^2 n)}\, e\sqrt{\frac{kT_e}{m_e}}$$

@ $R_o \sim 1\text{-}10\,\text{cm}$ $n_e \gtrsim 10^{12}/\text{cc}$

$$\therefore \boxed{I = (10^{-4}\text{-}10^{-6})\, V_e = 10 - 1{,}000\ A}$$

CAN INCREASE w 1) ELECTRON HEATING

2) $\phi > \phi_{ALFVEN} \Rightarrow$ IONIZATION
(IN SHEATH ?)

Figure 9

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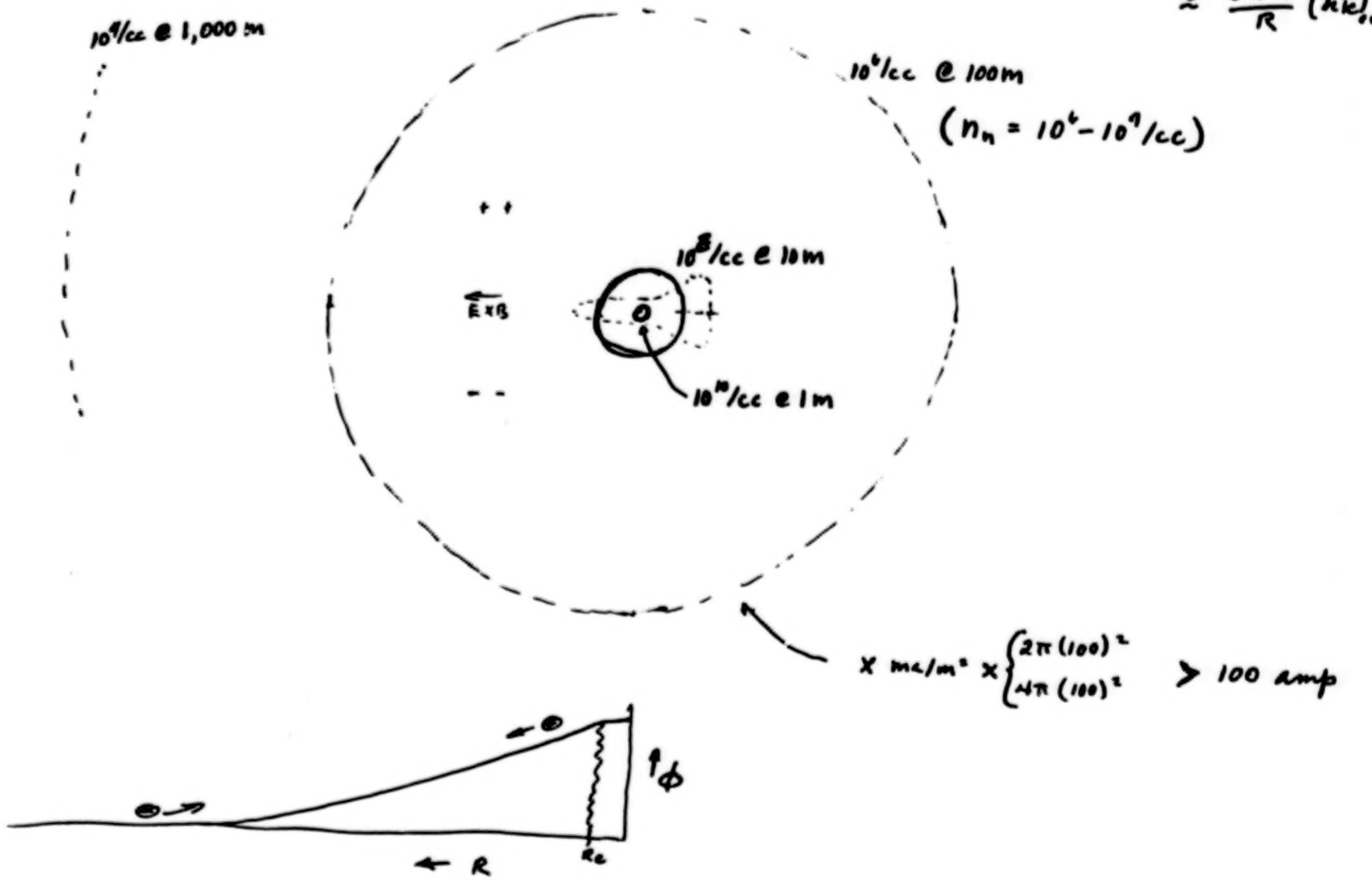
$$I_{Bohm} \approx e D_B \nabla n (4\pi R^2)$$

$$\approx \frac{5\times10^3}{R}(k\bar{T}_e)_{ev} \frac{n_0}{10^{14}}$$



10^4/cc @ 1,000 m
10^6/cc @ 100m
$(n_n = 10^6 - 10^9/cc)$
+ +
$\overleftarrow{E \times B}$
− −
10^8/cc @ 10m
10^{10}/cc @ 1m
$X \text{ ma/m}^2 \times \begin{cases} 2\pi(100)^2 \\ 4\pi(100)^2 \end{cases} > 100 \text{ amp}$
Φ
R_c
← R

Figure 10

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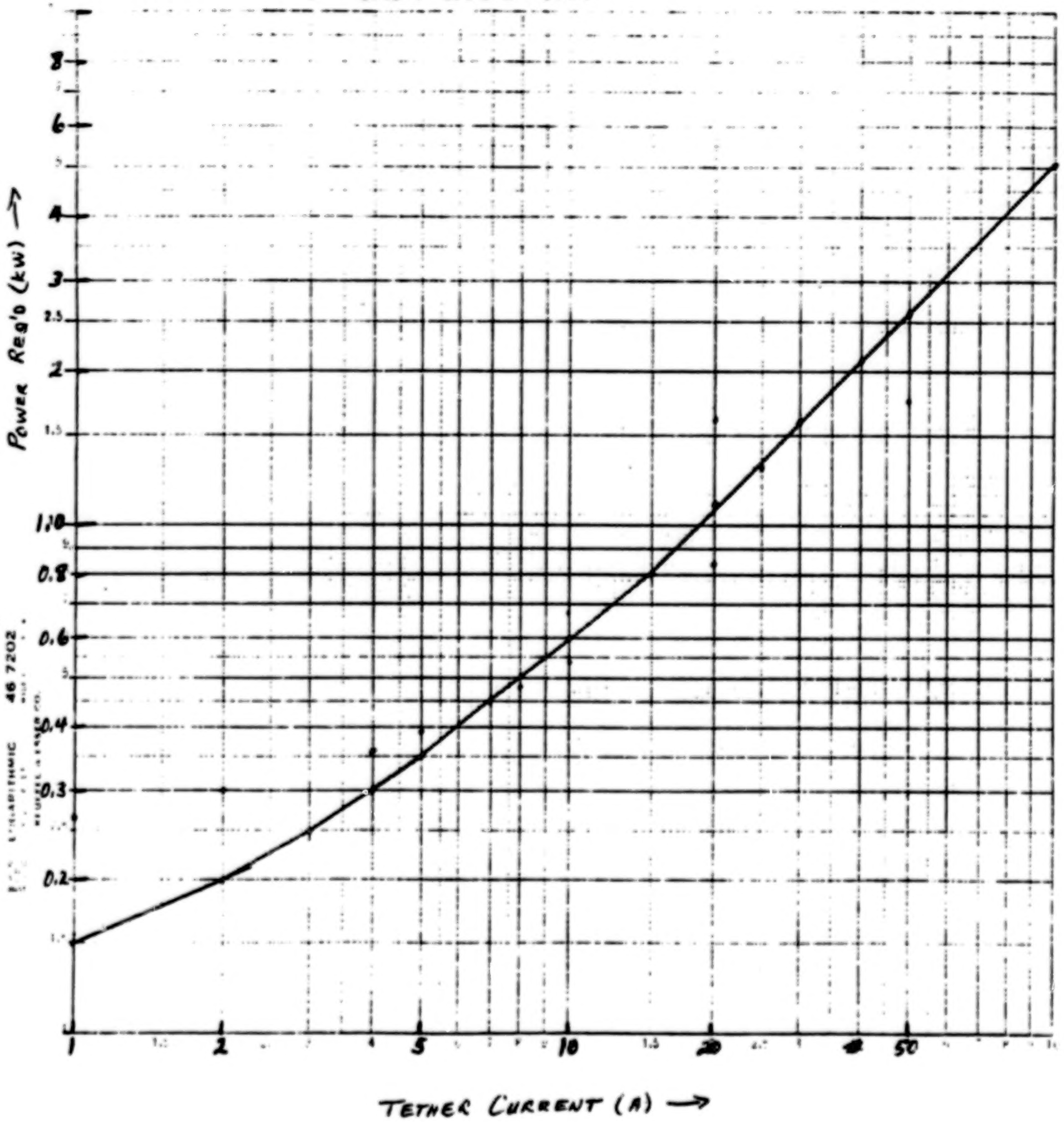
11/23

HOLLOW CATHODE "NEUTRALIZER"/"PLASMA BRUSH"

POWER REQ'D vs TETHER CURRENT

$P = 0.10 + 0.05\,I$ (kW)



COUPLED TO IONOSPHERE

Figure 11

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TETHER CURRENT vs POWER LOSS

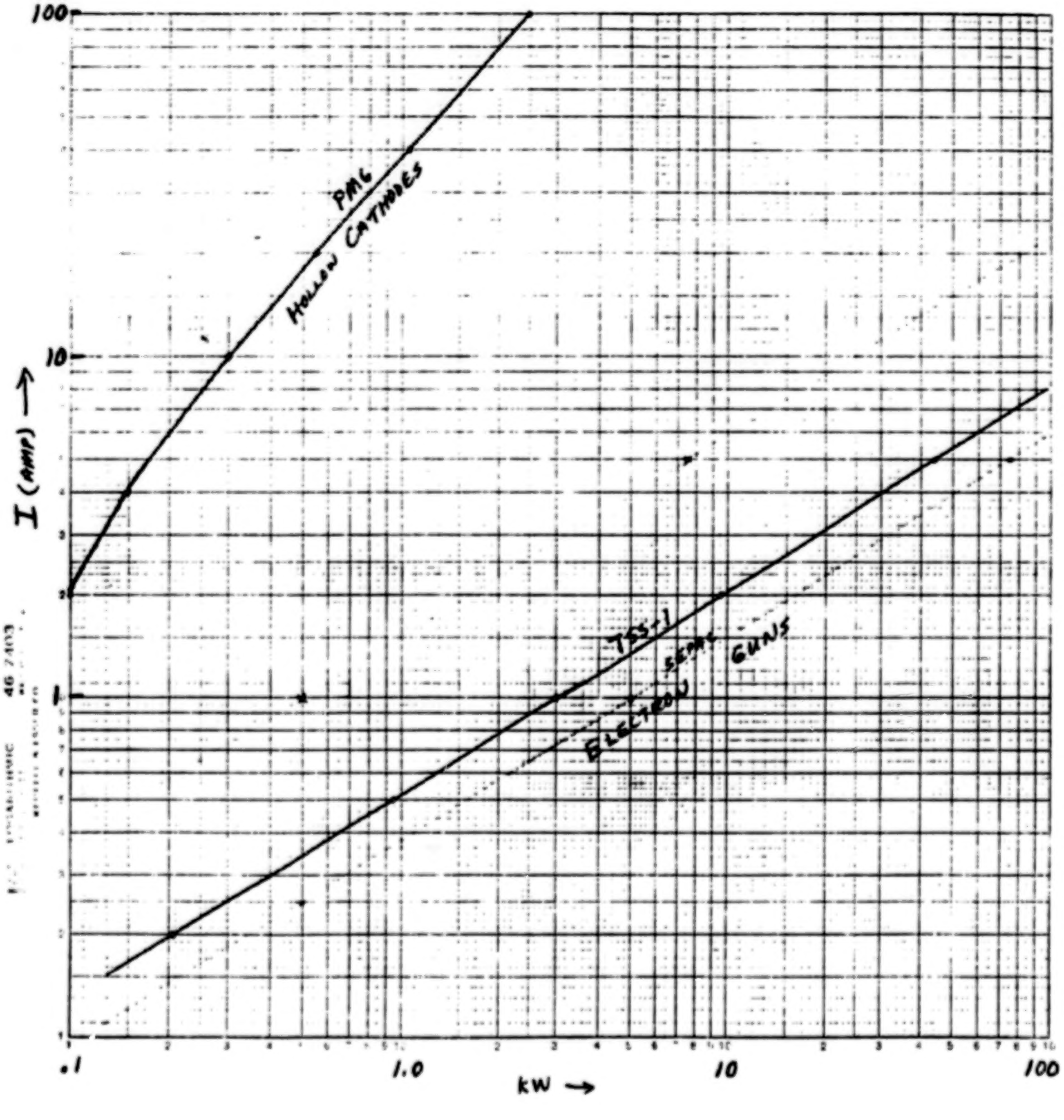

Figure 12

Power vs I

plus power req'd to create plasma, electrons, etc in absence of current

TETHER CURRENT vs. VOLTAGE LOSS

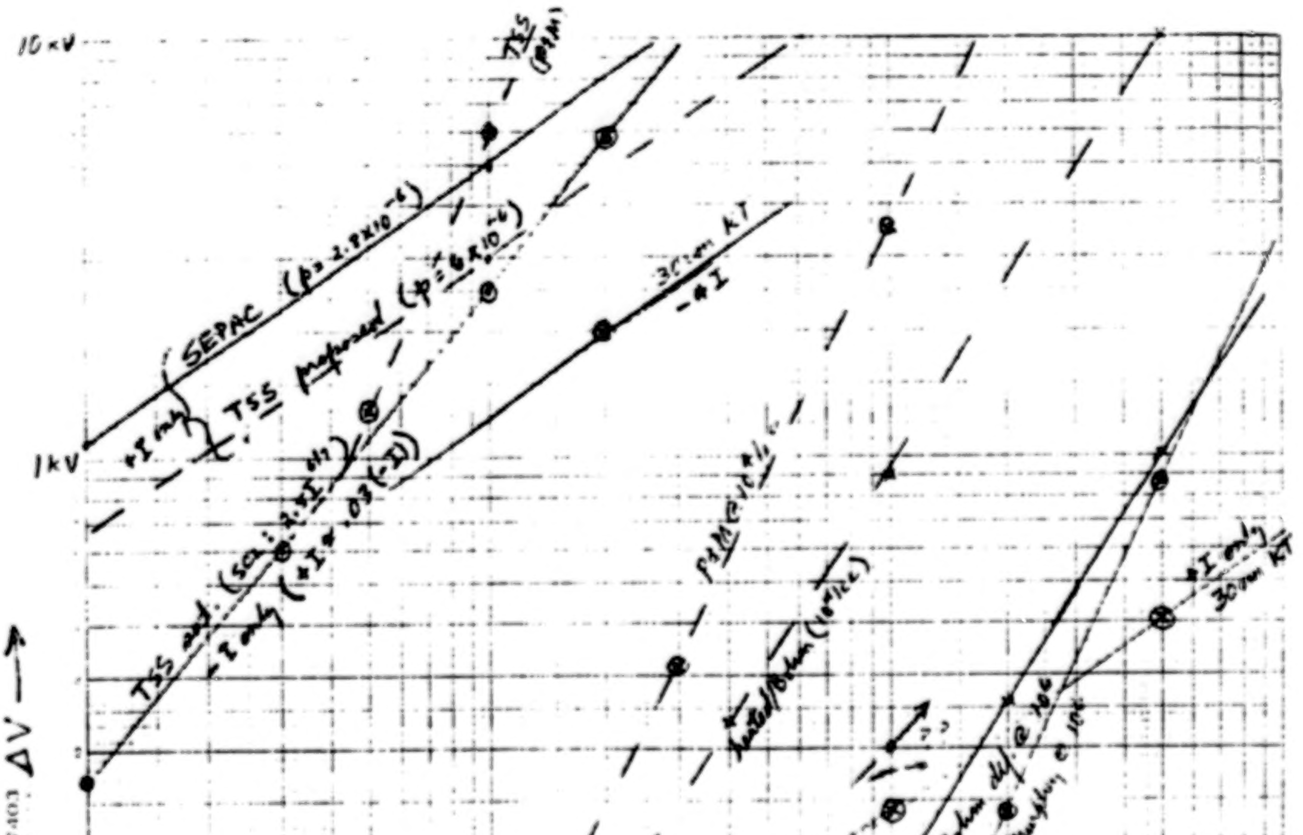

Figure 13

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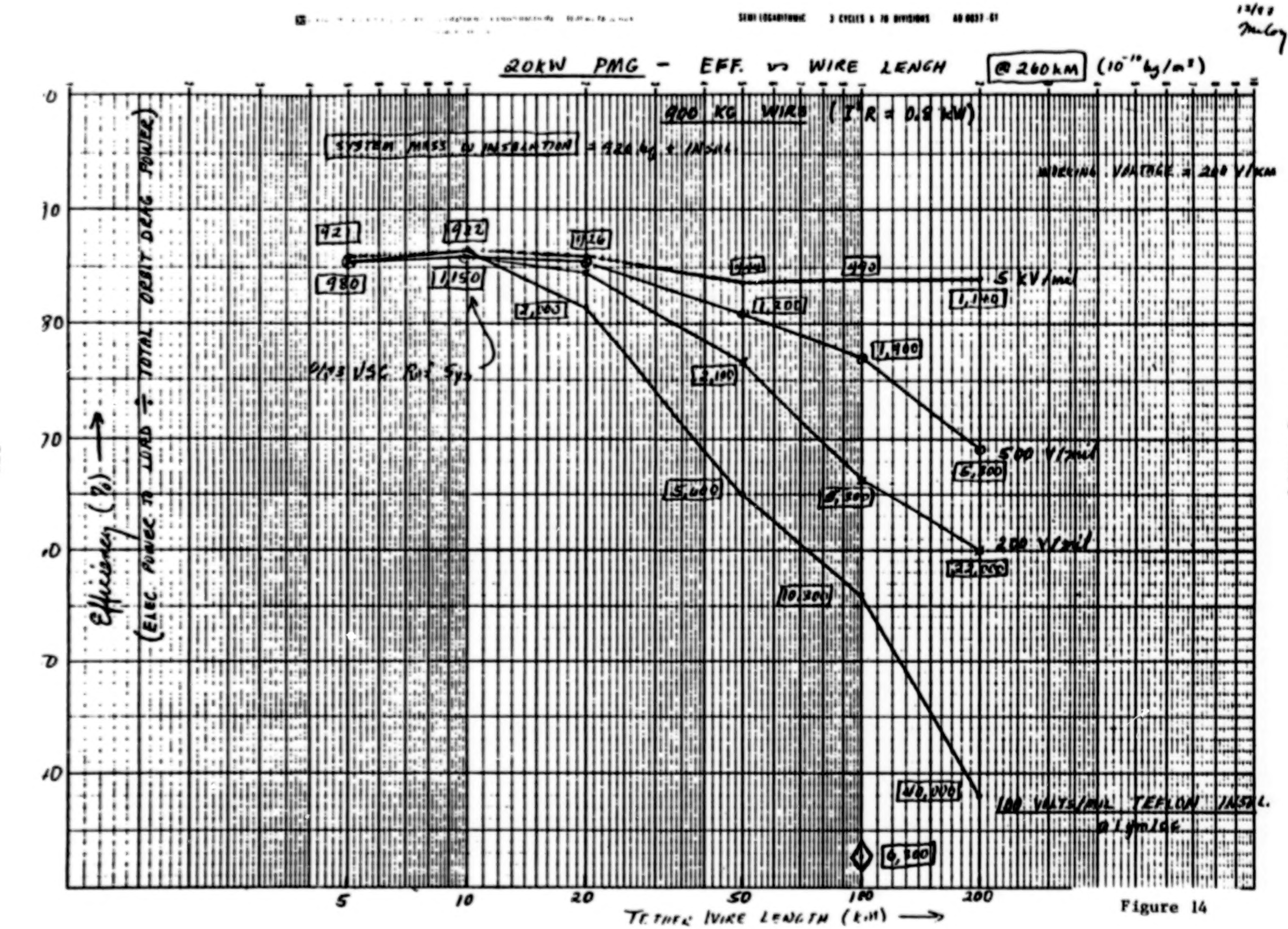

Figure 14

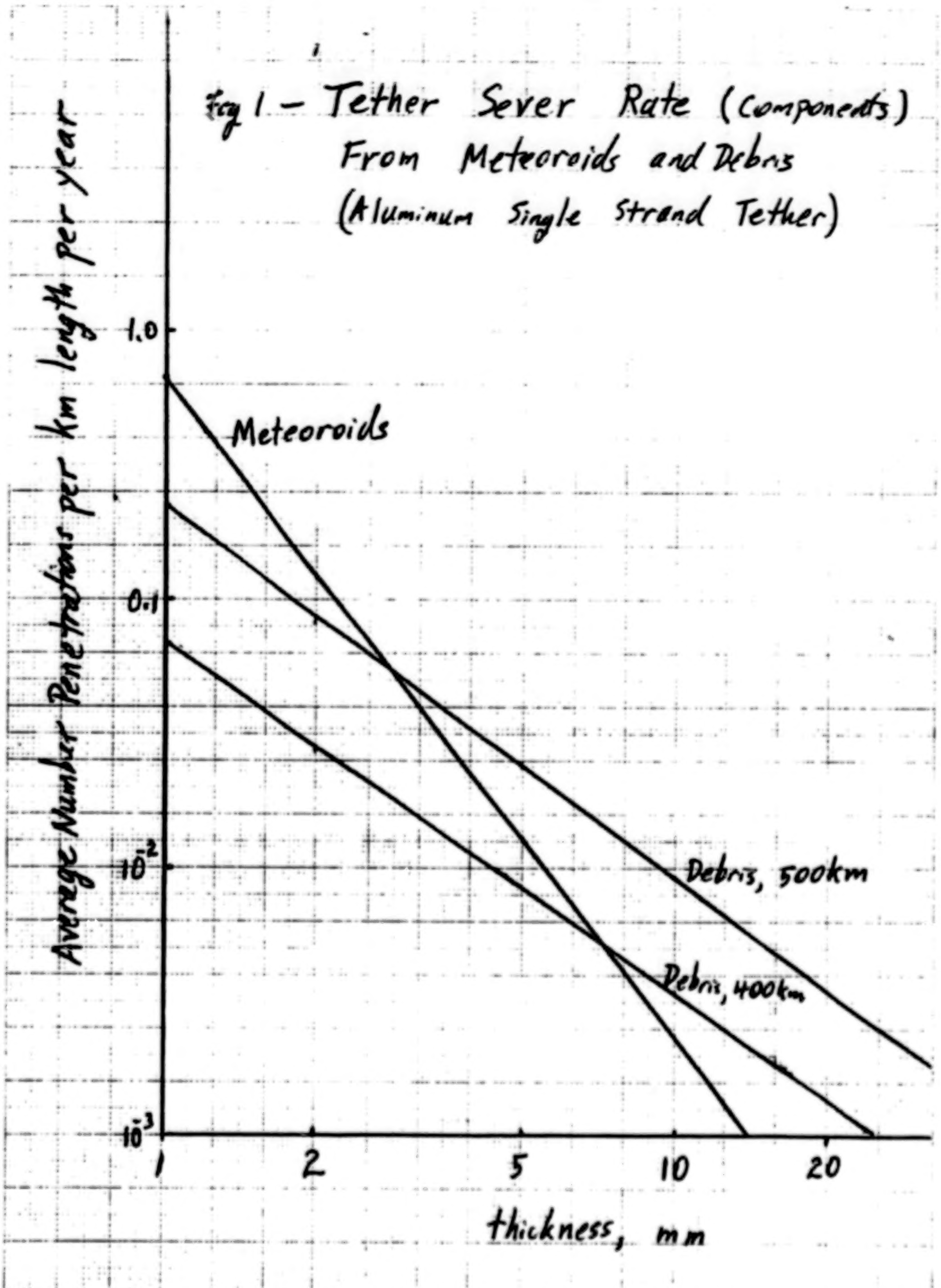

Fig 1 – Tether Sever Rate (Components) From Meteoroids and Debris (Aluminum Single Strand Tether)

Figure 15

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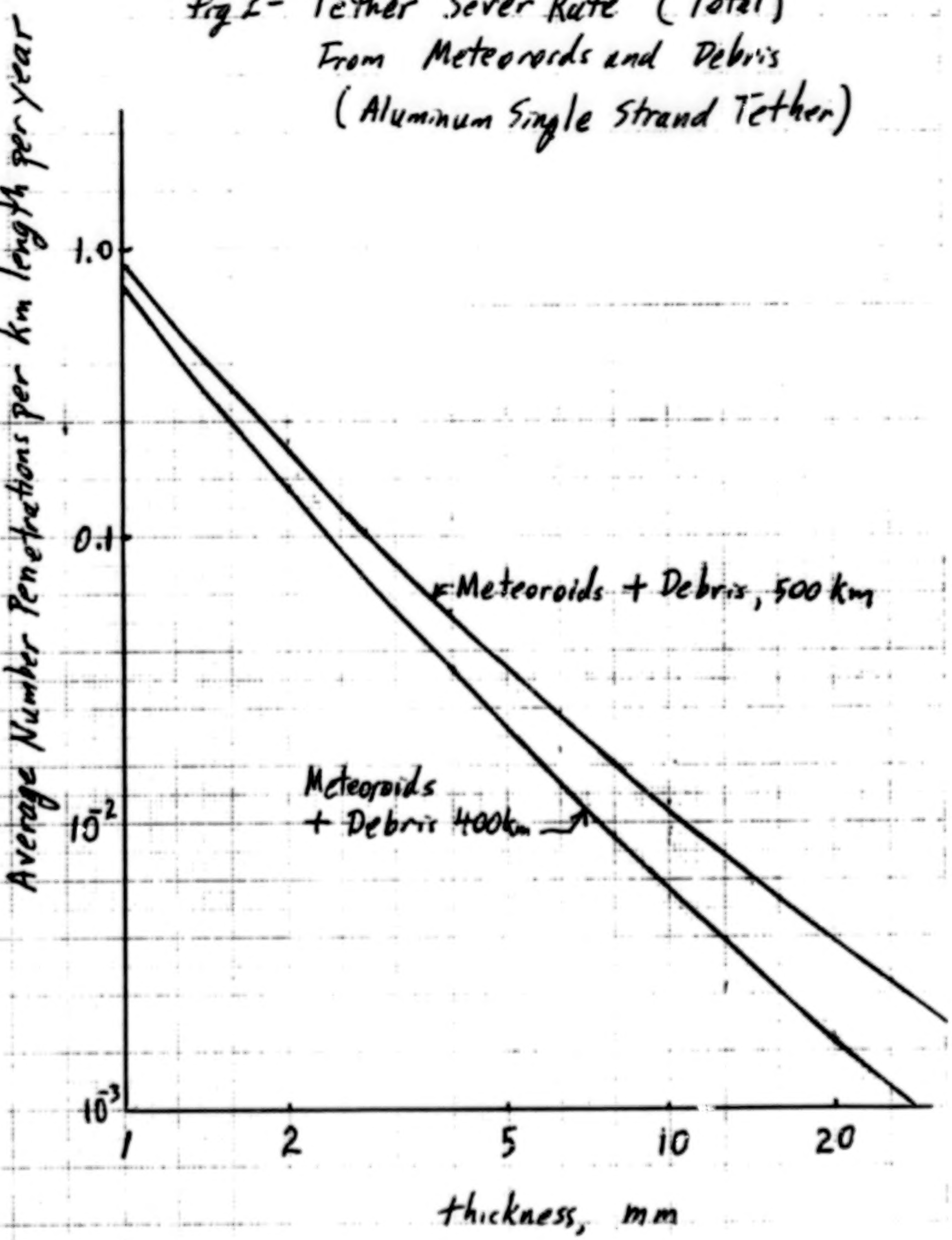


fig 2 - Tether Sever Rate (Total)
From Meteoroids and Debris
(Aluminum Single Strand Tether)

Figure 16

MASSIVE TETHER DYNAMICS

TETHER WIRE MASS: 10-10,000 KG/KM

"SATELLITE" MASS: 10 KG → 0

STRAIN ELONGATION MINOR EFFECT

WAVE PROPAGATION ALL MODES

- SHEAR
- COMPRESSION
- TORSION
- "STRING"

3-D OUT-OF-PLANE MAGNETIC & CROSS-COUPLE TERMS

RUNNING CONDITIONS

- ASSUME LOAD CONTROL REGULATION OF CURRENT (I)
  - CONSTANT I•V ⟷ IXB•L WITH VARIABLE B, VXB
- ALLOW ARBITRARY STEP CHANGES IN I•V
  - REFLECT "USER" LOAD DEMANDS
  - DAY/NIGHT CYCLE REVERSALS of POWER/THRUST
  - DYNAMIC CONTROL BY IXB PHASING ("CONTROL LAW")
  - ORBIT MANUEVER & CHANGE BY PHASED IXB THRUST
  - POWER STOREAGE/PROCESSING by I•V=d/dt(ORBIT)

APPLICATION

- STABILITY LIMITS - IMPORTANT FOR 5-20 KM TETHERS
- IXB THRUST INTEGRATION/TRANSFER TO SPACECRAFT
- MISSION PLANNING SIMULATIONS
- MISSION "REAL-TIME" OPERATION PLANNING/PROJECTIONS

Figure 17

FORCES IN TETHERED ORBITAL SYSTEM

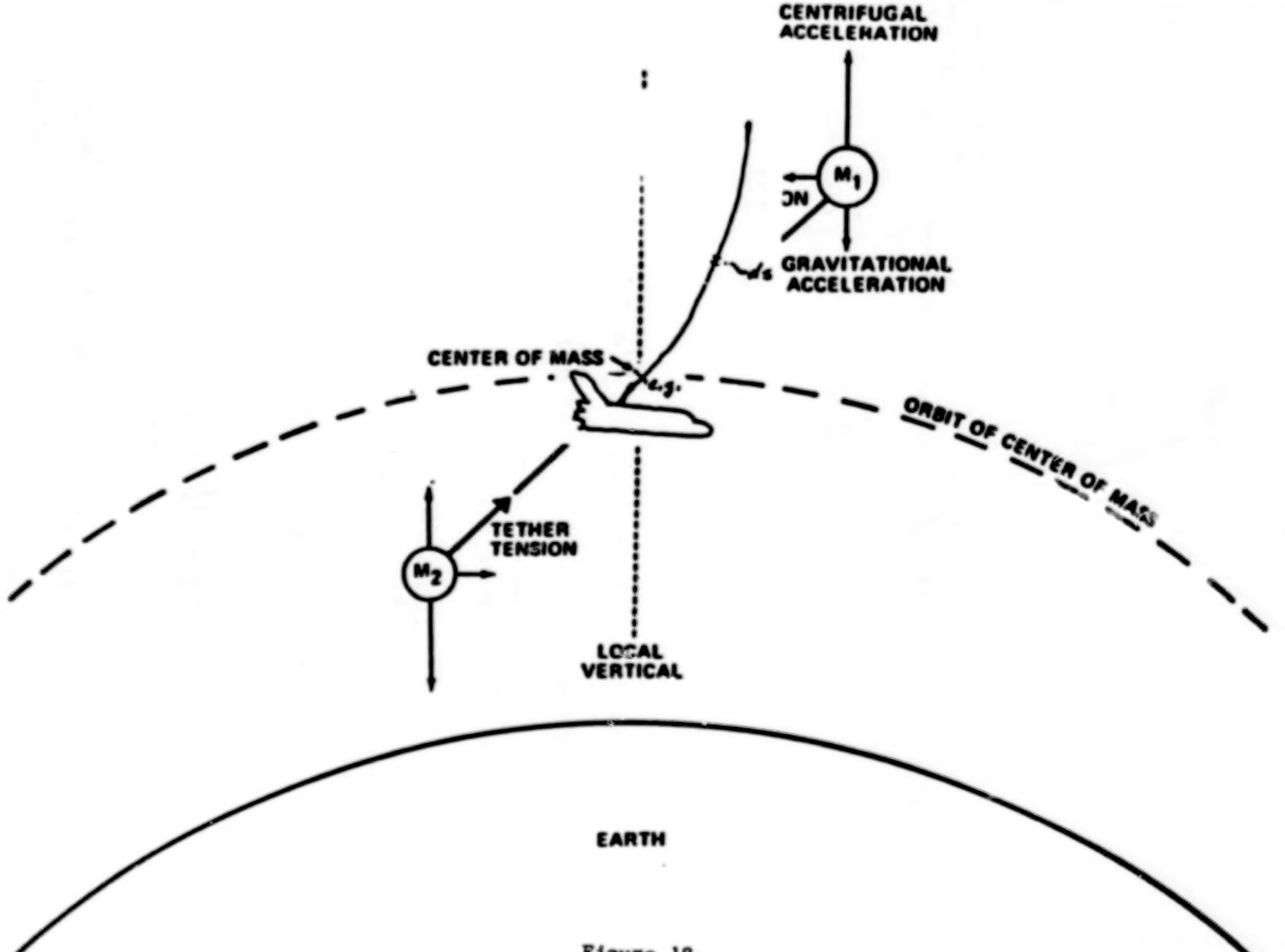
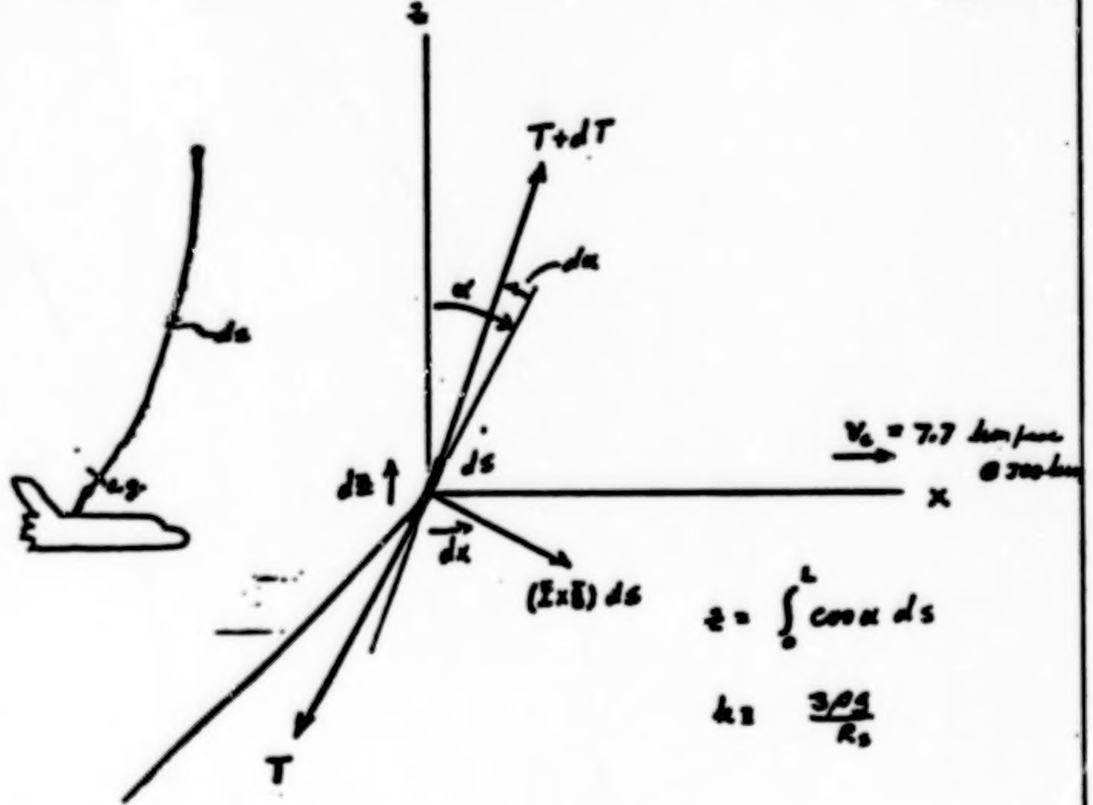

CENTRIFUGAL ACCELERATION
M_1
ON
ds
GRAVITATIONAL ACCELERATION
CENTER OF MASS
c.g.
ORBIT OF CENTER OF MASS
TETHER TENSION
M_2
LOCAL VERTICAL
EARTH

Figure 18

3

ELECTRO DYNAMIC TETHER

4/21/83
J. Mc Coy
NASA-JSC



$$z = \int_0^L \cos\alpha \, ds$$

$$k = \frac{3\rho g}{R_0}$$

(1) $k z \sin\alpha = IB + T\frac{d\alpha}{ds} \quad (+\sum_i F_{xi}\cos\alpha)$

(2) $k z \cos\alpha = dT/ds \quad (+\sum_i F_{yi}\sin\alpha)$

$$\boxed{\begin{aligned} T(z) &= T_0 + \tfrac{1}{2}k(z_L^2 - z^2) \\ \sin\alpha &= \frac{IB - T(d\alpha/ds)}{kz} \end{aligned}}$$

$$(C_1 - \tfrac{1}{2}kz^2)X_{zz} + kzX_z - IB = \rho X_{tt}$$

$$\boxed{\frac{\partial}{\partial z}\left[(1-\zeta^2)\frac{du}{dz}\right] + \frac{IB}{\rho} = u_{tt}}$$

Figure 19

$u(z,t) = g(t)\,\eta(z) + W(z)$

$W(z) = \frac{2IB}{3\rho\omega^2}\ln(1+\zeta)$

$g(t) = A_n\cos(\nu_n t) + B_n\sin(\nu_n t)$

$\zeta = \frac{z}{L}$ $\qquad \nu_n = \omega\sqrt{(3/2)\,n(n+1)}$

$\eta(z) = P_n(\zeta) \qquad n = \text{odd}$

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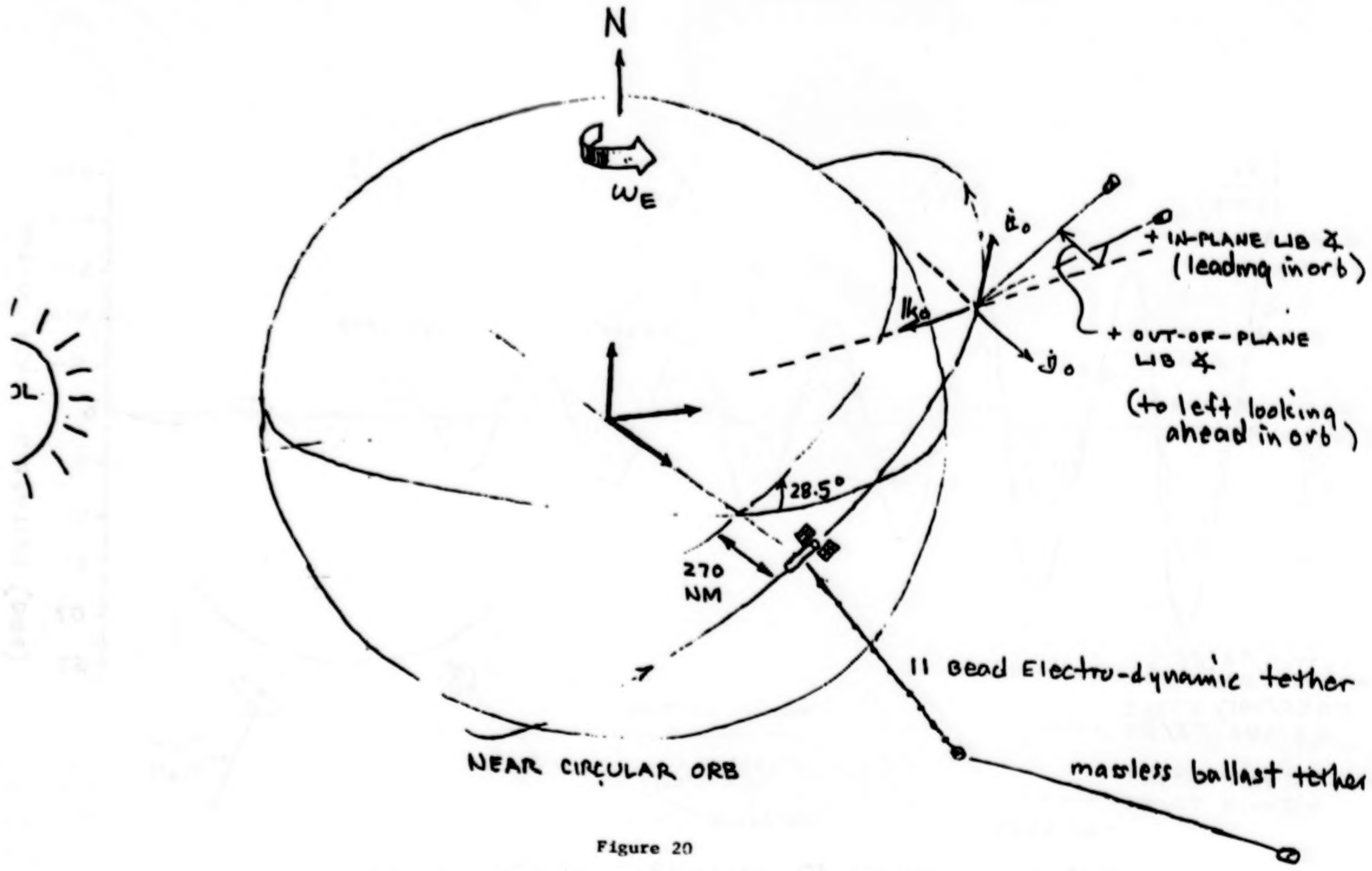
N
ω_E
i_o
+ IN-PLANE LIB ∡
(leading in orb)
k_o
+ OUT-OF-PLANE
LIB ∡
j_o
(to left looking
ahead in orb)
28.5°
270
NM
11 Bead Electro-dynamic tether
NEAR CIRCULAR ORB
massless ballast tether

Figure 20

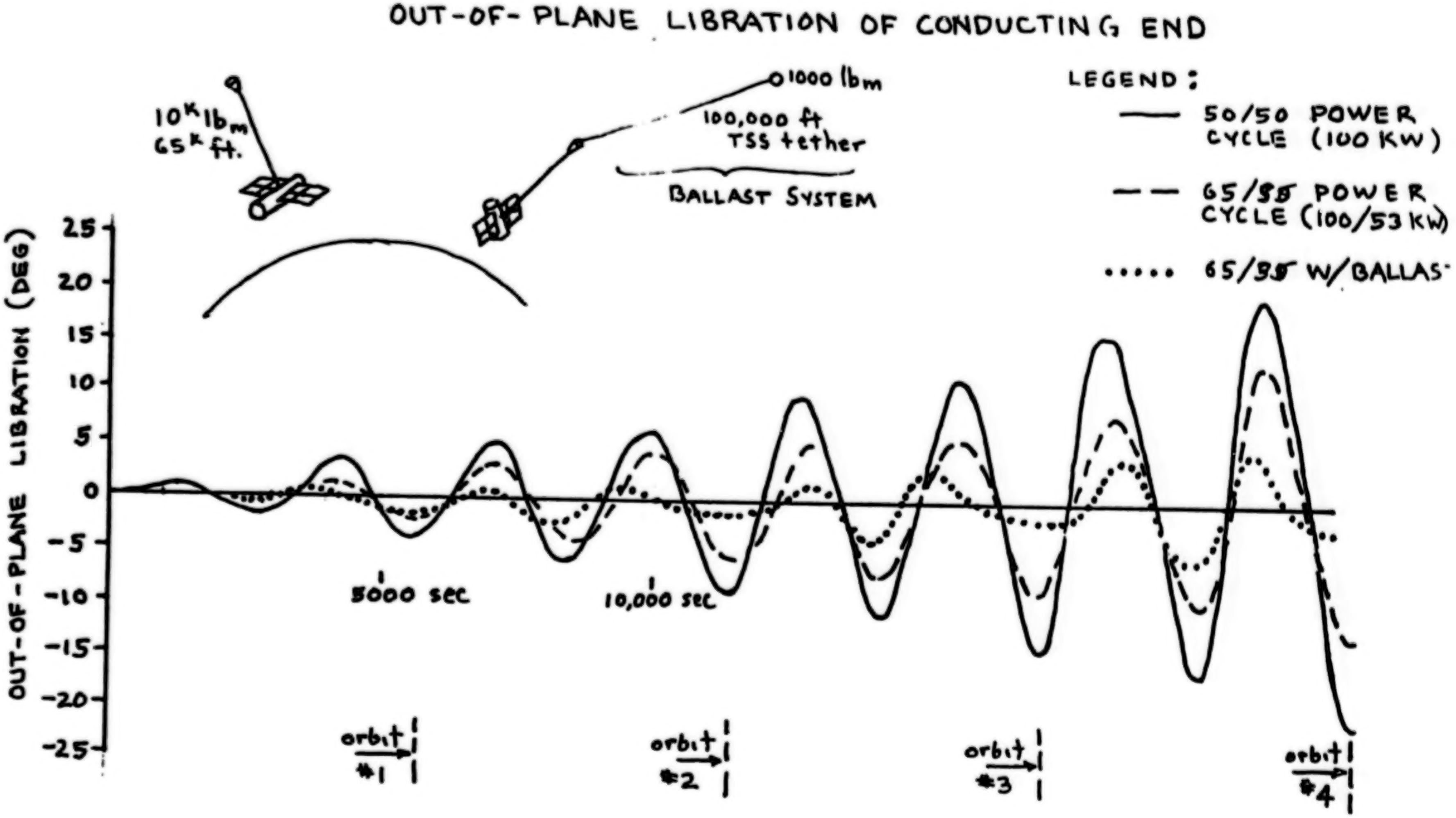
OUT-OF-PLANE LIBRATION OF CONDUCTING END
10K lbm
65K ft.
1000 lbm
100,000 ft
TSS tether
BALLAST SYSTEM
LEGEND:
50/50 POWER CYCLE (100 KW)
65/35 POWER CYCLE (100/53 KW)
65/35 W/BALLAS
OUT-OF-PLANE LIBRATION (DEG)
25
20
15
10
5
0
-5
-10
-15
-20
-25
5000 sec
10,000 sec
orbit #1
orbit #2
orbit #3
orbit #4

Figure 21

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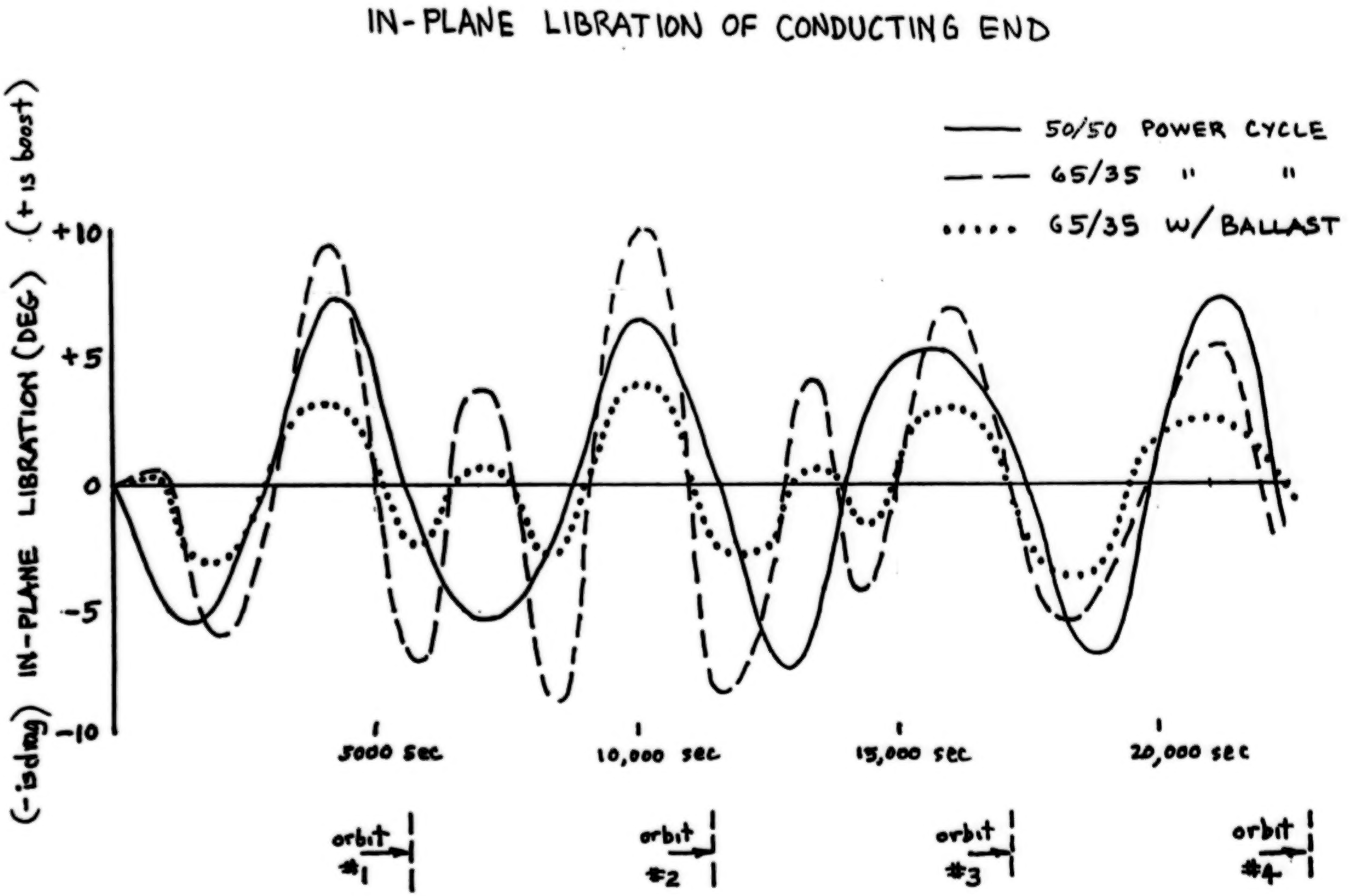

Figure 22

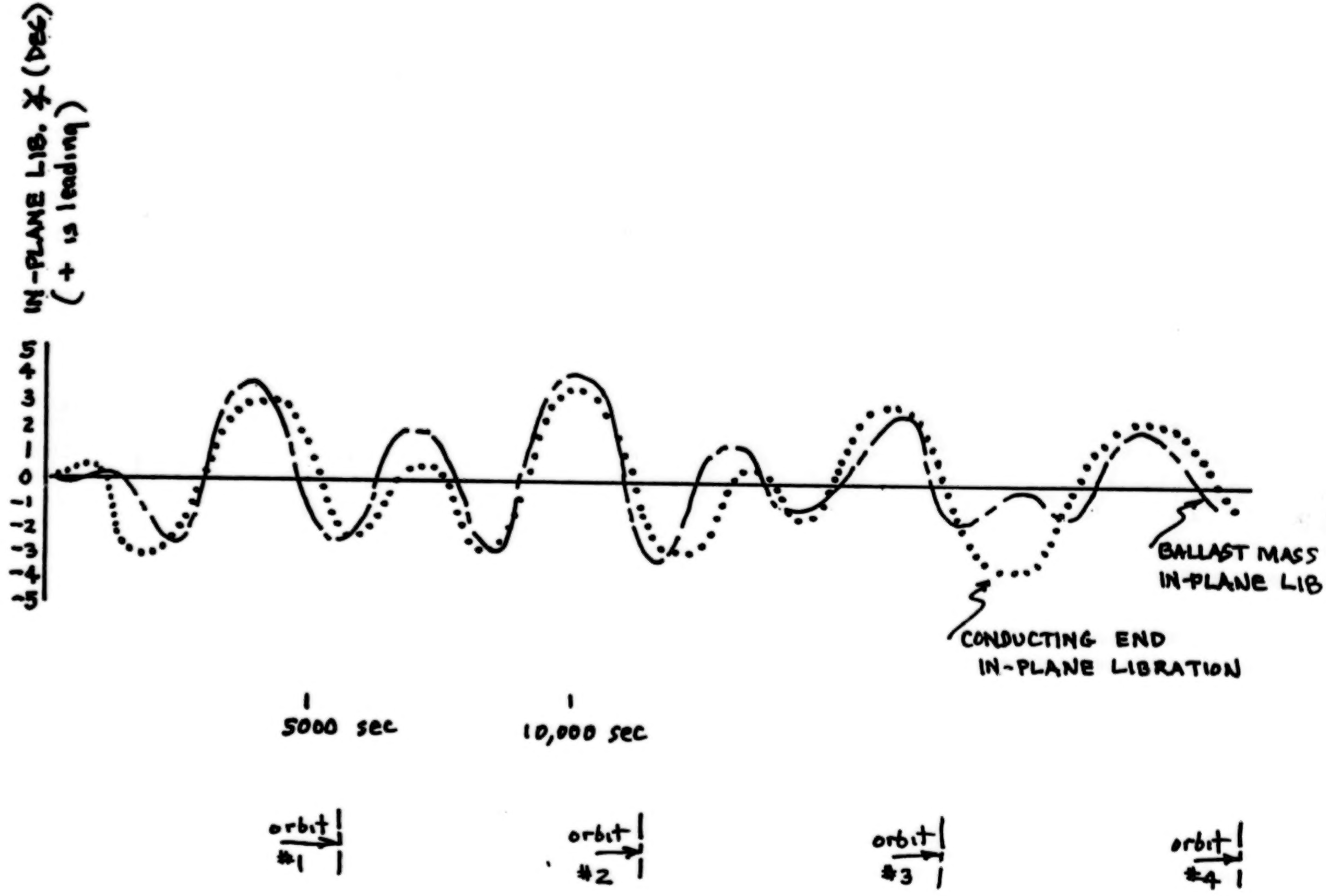
IN-PLANE LIB. ∡ (DEG)
(+ is leading)
5
4
3
2
1
0
-1
-2
-3
-4
-5
BALLAST MASS
IN-PLANE LIB.
CONDUCTING END
IN-PLANE LIBRATION
5000 sec
10,000 sec
orbit #1
orbit #2
orbit #3
orbit #4

Figure 23

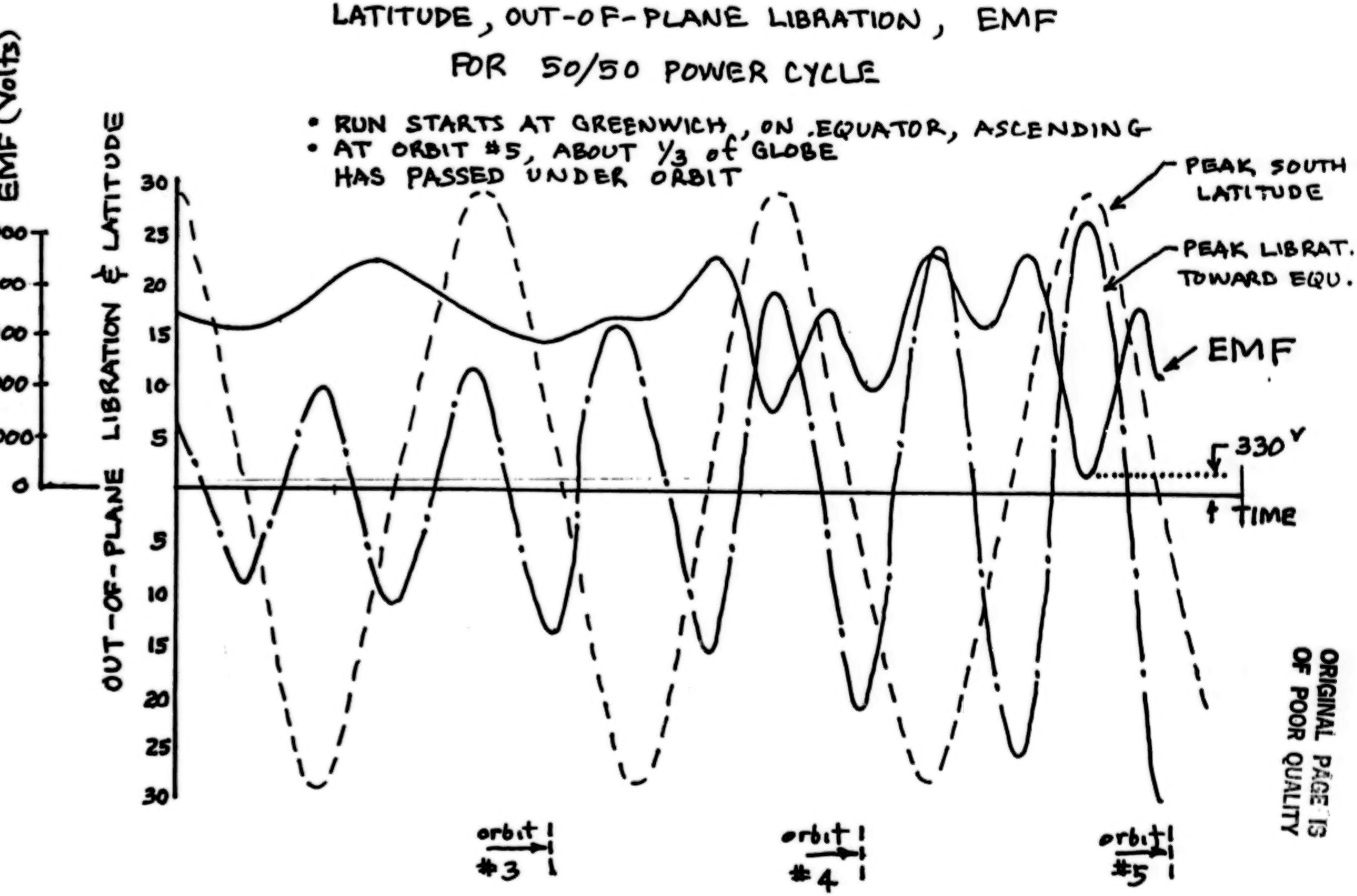

Figure 24

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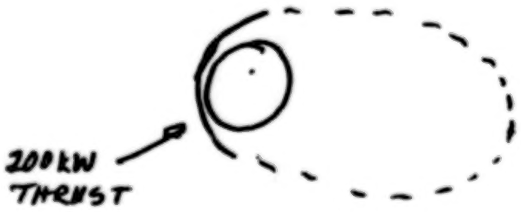
PMG TETHER WITH "BALLAST"

APPLICATION : HIGHLY UNSTABLE POWER CYCLES WHERE IXB PHASING INADEQUATE

1) $\frac{1}{2}$ ORBIT PERIOD OUT-OF-PLANE THRUST RESONANCE (PREVIOUS EXAMPLE)

2) LEO/GEO TRANSFER ORBIT "PUMPING"


200 KW
THRUST

2000 KG OTV : 6 DAYS @ 200 KW

PROBLEM: ANGULAR RATE IN XFER CONTINUOUSLY VARYING. (ω_0)

MUST KEEP TETHER (ω_T) IN PHASE

SOLN - RAPID VARIATION IN ANGULAR MOMENT. OF TETHER BY USING "BALLAST" SECONDARY TETHER AT END OF PMG TETHER

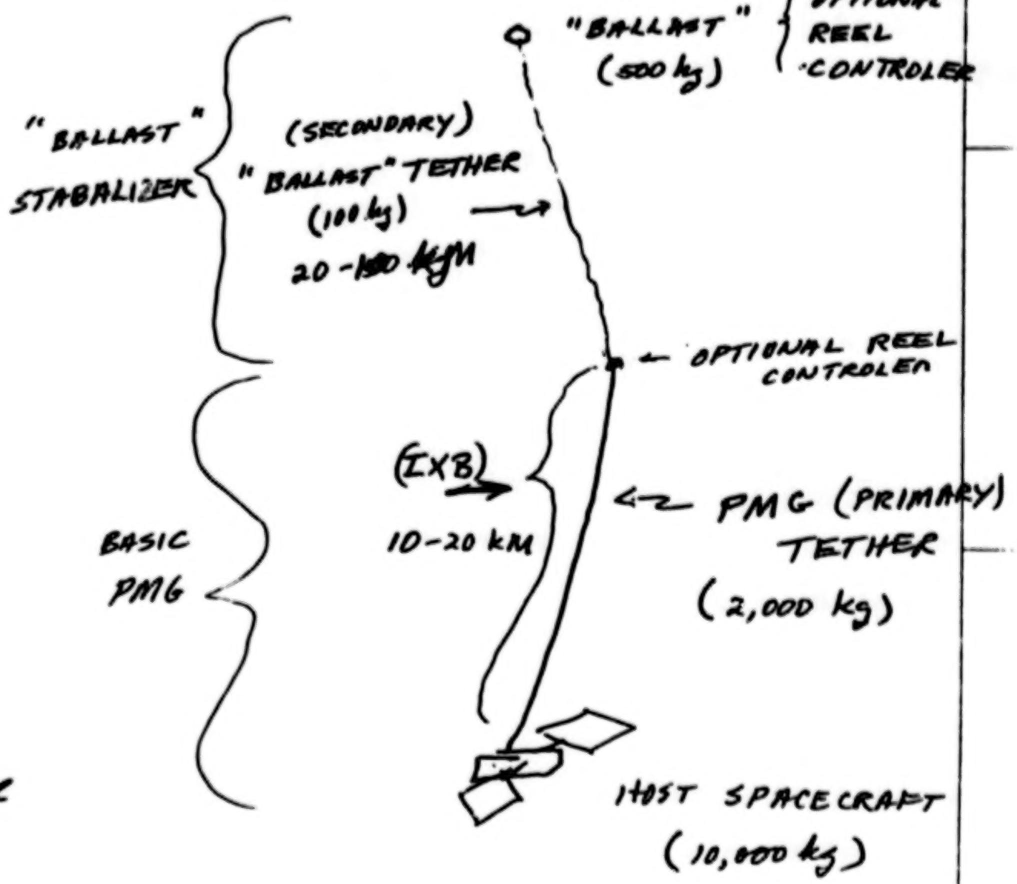

"BALLAST"
(500 kg)
OPTIONAL
REEL
CONTROLER
"BALLAST"
STABALIZER
(SECONDARY)
"BALLAST" TETHER
(100 kg)
20-100 KM
OPTIONAL REEL
CONTROLER
BASIC
PMG
(IXB)
10-20 KM
PMG (PRIMARY)
TETHER
(2,000 kg)
HOST SPACECRAFT
(10,000 kg)

Figure 25

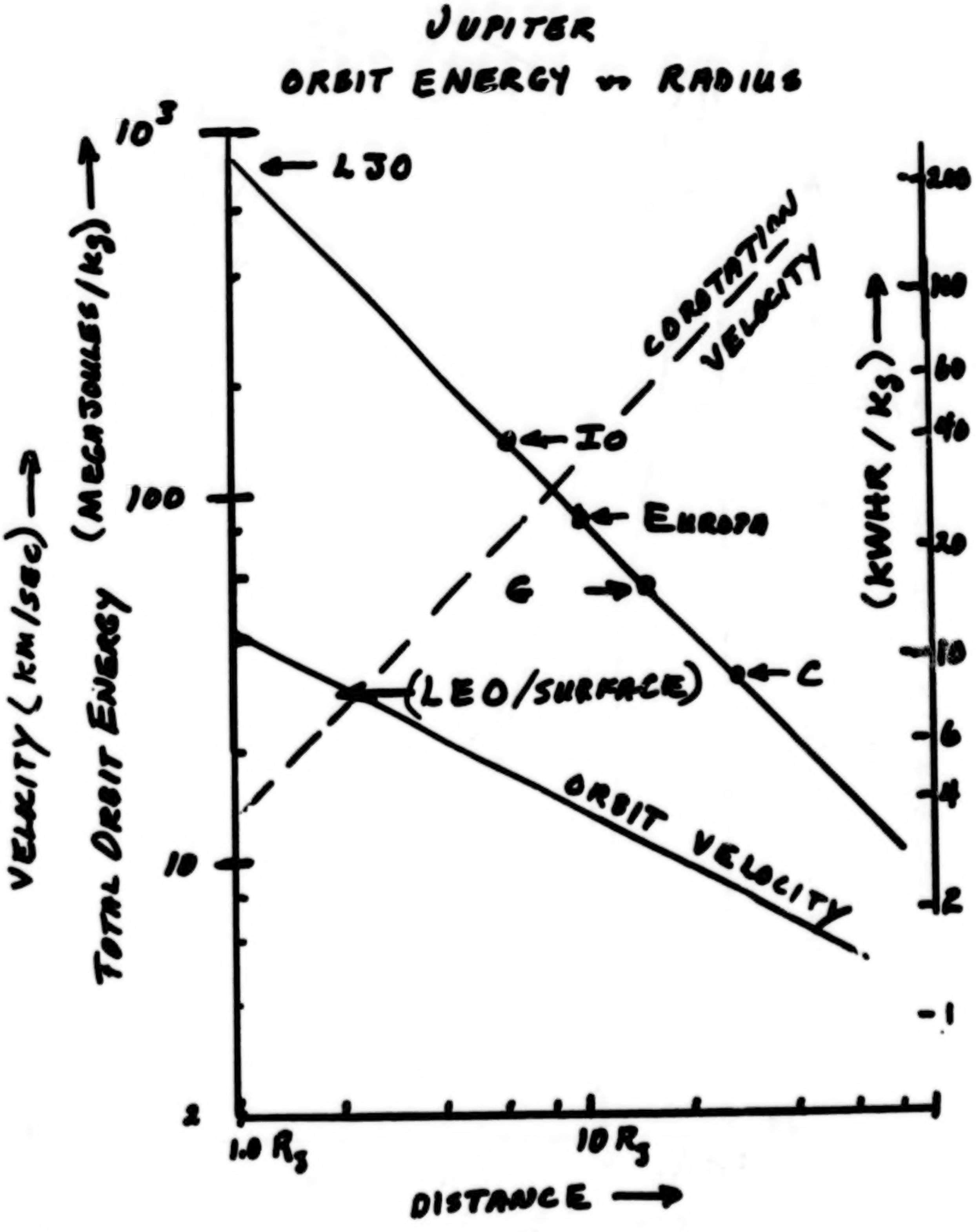

JUPITER
ORBIT ENERGY vs RADIUS
10³
100
10
2
LJO
Io
Europa
G
C
(LEO/SURFACE)
COROTATION VELOCITY
ORBIT VELOCITY
VELOCITY (KM/SEC) →
TOTAL ORBIT ENERGY (MEGAJOULES/Kg) →
(KWHR / Kg) →
200
100
60
40
20
10
6
4
2
1
1.0 R_J
10 R_J
DISTANCE →

Figure 26

TETHER VOLTAGE vs ORBIT RADIUS
[V= V_A sin θ]

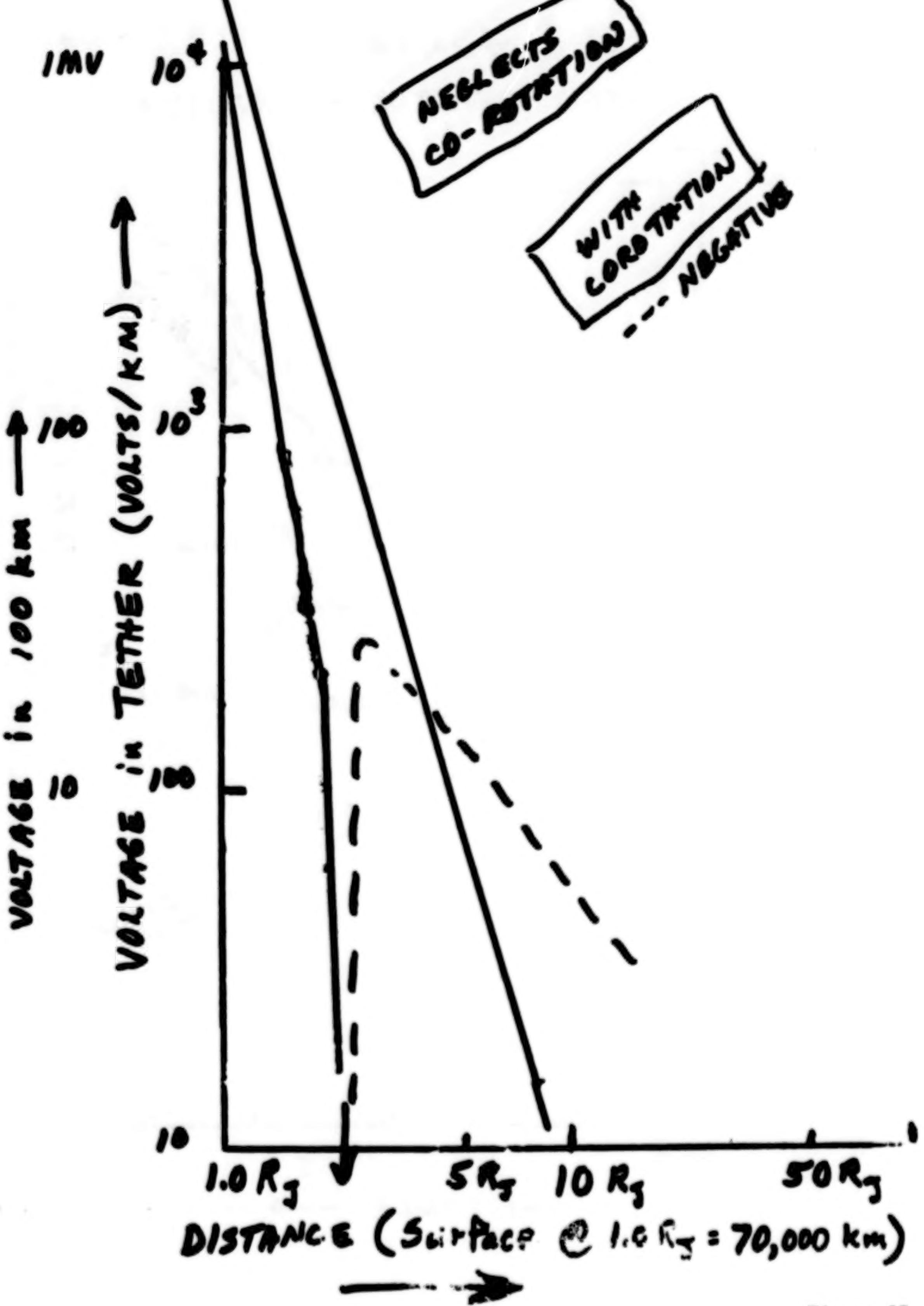


Figure 27

JUPITER ORBIT

TETHER TENSION vs DISTANCE (CIRCULAR) PG
&
THRUST/DRAG FORCE vs ORBIT DISTANCE

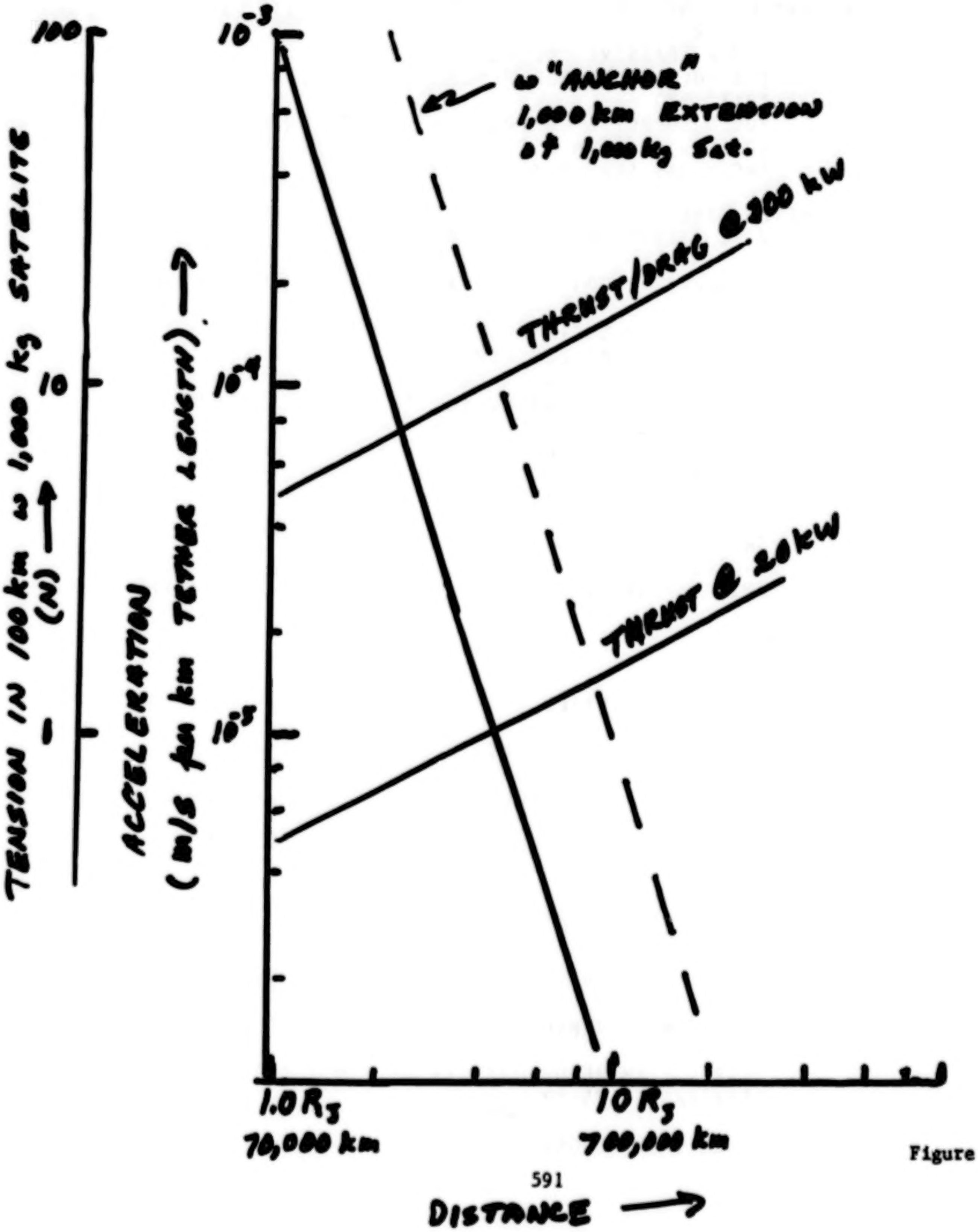


Figure 28

PMG/POF "EXPERIMENT OF OPPORTUNITY"

20 KG TOTAL MASS

- FAR END PACKAGE (FEP) 10 KG 15" DIA X 10" HIGH
    - $0.2\ M^2$ PASSIVE COLLECTION AREA
    - 1 A HOLLOW CATHODE PLASMA NEUTRALIZER
    - (BATTERY)
    - POWER SUPPLY & CONTROLLER for HOLLOW CATHODE
    - SPOOL with 200M #32 AWG COPPER WIRE
    - ARGON GAS SUPPLY & CONTROLLER
- 200 METER WIRE 0.4 KG TEFLON INSULATION
    - 2 lb "TEST" with 4 lb BREAKAWAY
- NEAR END PACKAGE (NEP) 10 KG 16" DIA X 28" HIGH
    - RETAINS FEP UNTIL RELEASE FOR DEPLOYMENT
    - 1 A HOLLOW CATHODE PLASMA NEUTRALIZER
    - BATTERY PACK (FLIGHT QUAL)
    - POWER SUPPLY & CONTROLLER for HOLLOW CATHODE
    - VARIABLE LOAD & PRECISION AMMETER
    - POWER SUPPLY to DRIVE MOTOR MODE CURRENT
    - PROGRAMABLE MICRO-PROCESSOR CONTROLLER
    - WIRE CUTTER for JETTISON
    - ARGON GAS SUPPLY & CONTROLLER
    - GROUND TEST PLUG
    - 3-WIRE (ON/OFF) CONTROL PLUG (GAS compatible)
    - RMS GRAPLING INITIATED RELEASE (FIXTURE MOUNTED on FEP)

DEPLOYABLE by RMS (COULD USE EVA/MMU IF EASIER)

- CENTRIFUGALLY STABILIZED @ 1 DEGREE/SEC = 0.6 N TENSION
    - via STS ORBITER STATION-KEEPING 200 M (-Z)
        (OMS) DELTA-V 3.5 M/SEC
        ROLL 1 DEG/SEC to keep FEP @ +Z ±30 DEG
- DEPLOYMENT SIMULATED SUCCESSFULLY AT NASA-JSC
    - MAX WIRE TENSION 1.2 N
    - AVERAGE WIRE TENSION 0.6 N

JETTISON AT END OF EXPERIMENT INTO NON-RECONTACTING ORBIT

- FROM 250 KM ORBIT, RAPID DECAY OF JETTISONED PACKAGE
    - DECAYS 1 KM BELOW ORBITER by FIRST CROSSING
    - REENTERS IN 25 HR
- NEP WITH ALL DATA RECORDED RETURNED TO LANDING BY STS ORBITER

Figure 29

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OF POOR QUALITY

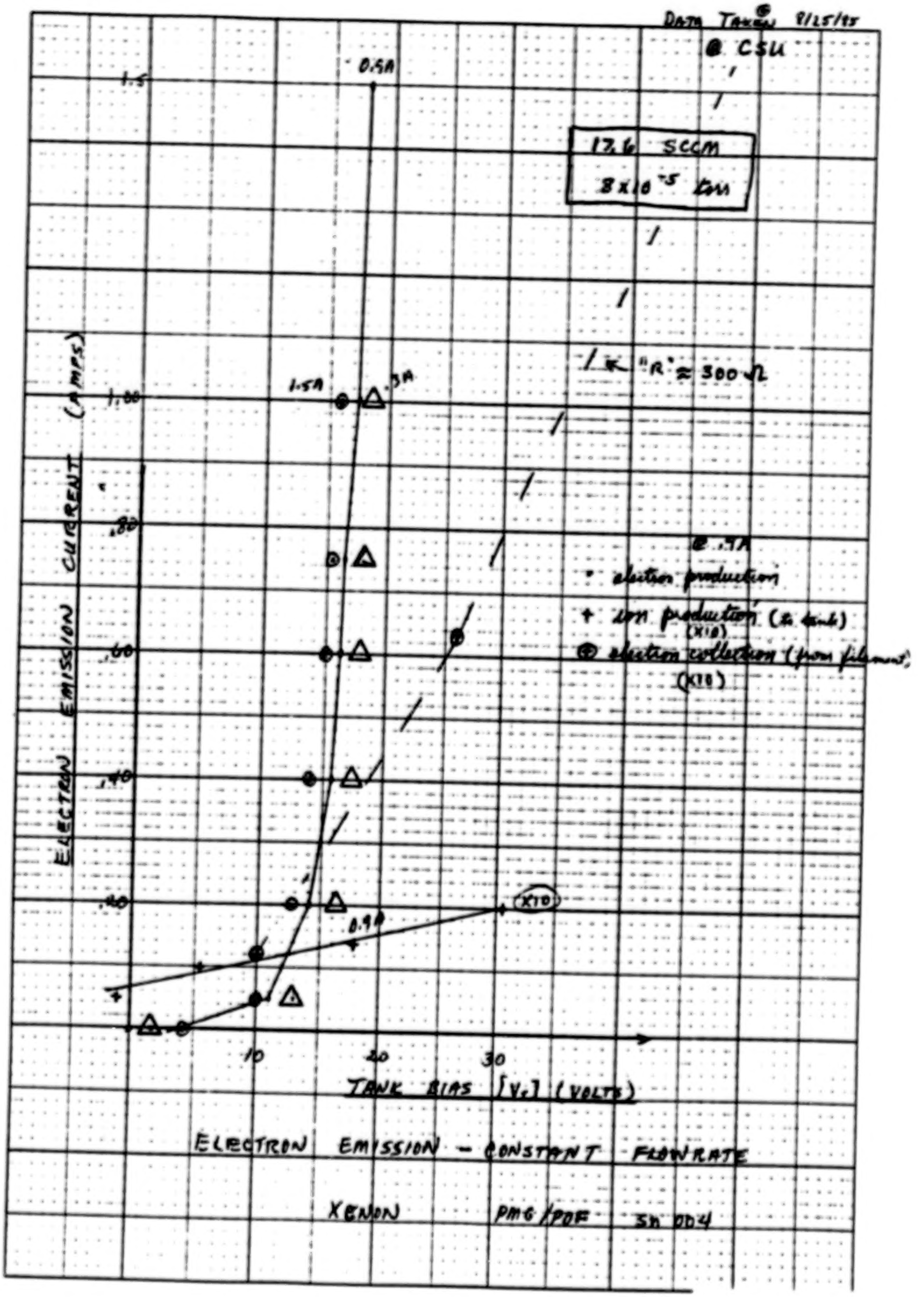
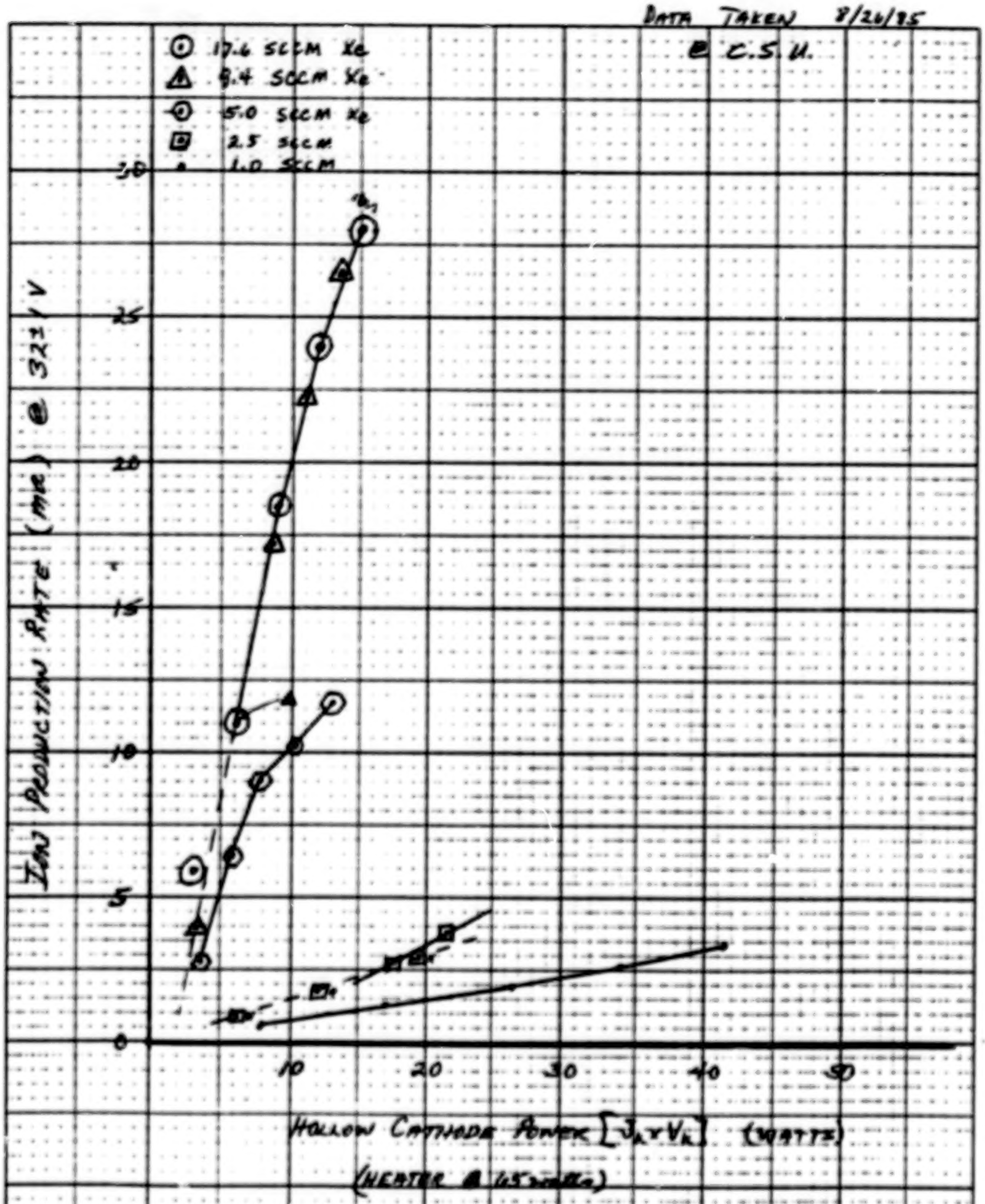


Figure 30



ION PRODUCTION RATE

JSC HOLLOW CATHODE (PMG/POP S.N. 004)

XENON

Figure 31

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16. Abstract

The proceedings of the second workshop on Applications of Tethers in Space, sponsored jointly by the Italian National Space Plan, CNR, and NASA, held in Venice, Italy, October 15-17, 1985, are presented here. The workshop was attended by persons from government, industry, and academic institutions to discuss the rapidly evolving area of tether applications in space.

This volume contains the complete documentation of the workshop, including opening addresses, tether fundamentals, and panel reports and summaries.

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